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REPORT

SYSTEMS ANALYSIS OF THE EFFECTS OF AIR POLLUTION ON MATERIALS

FINAL REPORT
15 June 1969 - 14 January 1970

Contract CPA-22-69-113

MRI Project No. 3323-D

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For

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The report describes research concerned with determining the economic effects of air pollution on materials. The research results constitute an important first step in providing economic justification for setting air pollution control standards and for implementing control regulations. The first three chapters of the report describe the methodology and approach used in conducting the research. The next three chapters present data on air pollutants and economically important materials. The following three chapters are concerned primarily with analysis of the data. The final chapter offers conclusions drawn as a result of the over-all research program, and identifies areas where further action is warranted.

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PREFACE

This report, "Systems Analysis of the Economic Effects of Air Pollution on Materials", was prepared by the Midwest Research Institute pursuant to Contract CPA 22-69-113 with the National Air Pollution Control Administration, Public Health Service, United States Department of Health, Education and Welfare.

Many members of the Institute staff contributed to this research. A Review Committee composed of senior chemists, chemical engineers, physicists, and metallurgists provided guidance, criticisms, and consultation on especially difficult aspects. Richard Salmon was Project Director, Dr. George Beitel had primary responsibility for physical and chemical analyses. Dr. Chatten Cowherd also contributed heavily to these analyses. William Park, Senior Engineering Economist, did the economic analyses, assisted by Marc Semanoff. Gordon Gross, Head of the Physics Section, contributed valuable criticism and guidance. Dr. Thomas Bath assisted with interviews in the Washington, D. C., area which yielded significant information.

We must also acknowledge the valuable contributions, discussions, expert opinions and other help we received from engineers and scientists throughout the nation. The list is too long to enumerate--S. K. Coburn, Dr. Salvin, Dr. McCabe, H. C. Wohlers, and many others.

We sincerely believe that the findings herein will contribute to the clarification and, finally, the solution of a serious national problem.

Approved for:

MIDWEST RESEARCH INSTITUTE

John McKelvey, Director
Economics and Management Science
Division

15 January 1970

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SUMMARY

The research described in this report is concerned with determining the economic effects of air pollution on materials. The information thus developed constitutes an important first step in providing economic justification for setting air pollution control standards and for implementing control regulations.

The report is divided into several broad sections. The first three chapters describe the methodology and approach used in conducting the research. The next three chapters present data on air pollutants and economically important materials. The following three chapters are concerned primarily with analysis of the data. The final chapter offers conclusions drawn as a result of the over-all research program, and identifies areas where further action is warranted.

A brief summary of the highlights from each chapter follows.

Chapter I - Introduction

The project involved a 13-task study plan, grouped into four distinct phases: (1) problem refinement; (2) information gathering; (3) analysis; and (4) documentation.

Chapter II - The Approach to Economic Effects Determination

Economic losses can be caused by either the physical deterioration of a material or by soiling. In either case, the economic effect of air pollution on a material is a function of two important factors: (1) the total value of the material exposed to air pollution; and (2) the reactions that take place between the exposed material and the air pollutants to which it is exposed.

Chapter III - Data Collection Plan

Data were collected by a thorough literature search and by interviews with knowledgeable individuals. In all, several thousand documents were reviewed, and a bibliography of more than 300 pertinent documents was developed. Each item in the bibliography was cataloged and coded on edge-notched cards for quick access by subject. The quality of each bibliographic reference was also assessed.

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Chapter IV - Intensity of Air Pollution

Typical concentrations of significant gaseous and particulate air pollutants were developed for representative urban and rural environments. The gaseous pollutants considered included organic gases such as hydrocarbons; and inorganic gases such as oxides of nitrogen, sulfur and carbon. The composition of particulate pollution is discussed.

Chapter V - Physical/Chemical Effects of Air Pollutants on Materials

Effects of air pollution on materials range from soiling to chemical alteration. Corrosion of metals has attracted the most attention, while many other important areas were found to have been largely neglected. The chemical resistance of important materials to various air pollutants was estimated, and the manifestations of chemical attack by pollutant gases on various materials were categorized. Most materials exhibit a high degree of chemical resistance to oxides of nitrogen, while sulfur oxides were found to seriously attack about a third of the materials. And while some materials (such as glass) are highly resistant to chemical attack by most air pollutants, certain plastics and metals are highly susceptible to damage by a number of different commonly encountered air pollutants.

Chapter VI - Economic Value of Materials Exposed to Air Pollution

The economic value of a material exposed to air pollution is the product of its annual production value, its economic life, a labor content factor to reflect its in-place value, and its degree of exposure. The resulting total economic value of 53 important materials was thus calculated. Cement and concrete are by far the most important materials, with $316 billion exposed to air pollution. Other economically important materials from the standpoint of their potential susceptibility to air pollution include copper ($55 billion); aluminum $54 billion); brass and bronze ($33 billion); glass ($29 billion); and zinc ($27 billion). These six materials account for nearly three-fourths of the approximately $700 billion worth of exposed materials specifically identified in this study.

Chapter VII - Interactions between Pollutants and Materials

The economic damage caused by exposure of a material to air pollution depends not only on the material's value, but also upon the characteristics of that material's reaction to the polluted environment. In damage caused by soiling, the value of interaction reflects the incremental frequency and cost of cleaning the material to maintain it in a state of cleanliness comparable to what would be expected in an unpolluted environment.

For damages caused by corrosion or other forms of chemical or physical deterioration, the interaction value measures the annual loss of material. Interaction values for both soiling and deterioration were developed for all 53 of the economically important materials identified in the preceding chapter.

Chapter VIII - Significance of Pollutant-Material Combinations

Economic damage caused by the exposure of materials to air pollutants is calculated as the product of the economic value of the exposed materials and their interaction values for soiling and deterioration. All 53 of the identified materials were ranked in order of their economic losses. An estimated $100 billion in added cleaning costs would be necessary to keep these materials in polluted areas as clean as they would be in a nonpolluted environment, while deterioration of these materials causes yearly direct damage losses of approximately $4 billion. Paint and zinc are the two materials most affected by both soiling and deterioration caused by air pollution, accounting for more than half of the total losses in each category.

Chapter IX - Identification of Information Gaps

By comparing the relative importance of the materials (measured in terms of their respective economic losses caused by the soiling and deterioration effects of air pollution) with the amount and quality of information available on each material, the most significant information gaps can be easily identified. The lack of useful data was particularly noticeable with respect to cement and concrete, fibers and plastics.

Chapter X - Conclusions and Recommendations

Adequate information on the economic effects of air pollution is presently available concerning only a very few material-pollutant combinations. Nevertheless, economic losses resulting from soiling and deterioration of materials by air pollutants can be estimated; these losses total $100 billion from soiling (estimated cost required to keep materials in polluted areas as clean as they would be in a nonpolluted environment), and $4 billion from deterioration. There is still, however, a real need for more precise data on the physical, chemical, and economic aspects of pollutant-material interactions, as well as for better ways of obtaining the data. A three-phase research program is recommended, consisting of (1) improved techniques for quantifying the economic effects of air pollution on materials; (2) development of physical and chemical data on air pollution effects; and (3) continuation and refinement of the economic evaluation of these effects.

CHAPTER I

INTRODUCTION

BACKGROUND

Economic justification of air pollution control measures is difficult. For many areas, such as health and agriculture, information is not available because techniques have not been developed to identify and measure the effects of air pollution. The need for such justification is great, however, and a logical first step is to determine that which can most readily be determined: materials damage.

The following sections of this report present an approach to measuring materials damage attributable to air pollution. The program has been designed using the systems analysis approach. This approach includes a classification of materials, a classification of air pollutants, and an enumeration of the possible chemical and physical interactions of air pollutants and materials that produce direct or indirect economic damages.

Other influencing variables such as time, meteorology, and degree of exposure to the atmosphere are identified whenever possible. In this study, information gathered from all available sources yielded the important variables involved, and provided a basis for assessing the credibility of the source and the data. Information gaps or items of questionable credibility are logical candidates for future research and development programs.

This research and development program identifies pollutant-material combinations that result in significant economic loss. Most of the research efforts on the potential sources of information, and on further research and development, should be directed toward only the more promising programs thus identified. Those programs should yield information useful as economic justification for setting air pollution control standards and for implementing control regulations.

OBJECTIVES

The overall objective of this project was ~~to conduct a research program~~ to determine the effects of air pollution upon materials. The specific objective for this project was a systems analysis of all the variables that should be considered in determining the economic effects of air pollution on materials. The objectives of the research program were:

1. Identification of materials, air pollutants, and environmental parameters that should be studied in order to assess the economic damage of materials caused by air pollution.

2. Systematic analysis of the physical and chemical interactions among the variables identified in (1) for the purpose of determining cause-effect relationships.

3. Determination, where possible, of the pollutant dosage-material response relationship for materials ~~that are~~ significant ~~because of their relative~~ economic value, and indication of how this may be done where such relationships are presently undefined.

4. Translation of the pollutant dosage-material response relationship into a pollutant dosage-monetary damage function that can serve as a basis for economic justification of air pollution control.

STUDY PLAN

This project consisted of four distinct phases: (1) problem refinement; (2) information gathering; (3) analysis; and (4) documentation. The major tasks involved in each phase are briefly described in the following sections.

Problem Refinement

Identification of the effectivity matrix: Certain materials are very seriously affected by relatively low concentrations of specific pollutants. This poses a significant problem only insofar as that use of that material is economically significant. Conversely, other materials may suffer only minor deterioration from a particular class of pollutants, but nevertheless pose a serious problem because of extensive and widespread use.

In a systems approach to the analysis of the effects of air pollutants on materials, a primary requirement is to visualize correctly the entire problem.

A multidimensional effects matrix conveniently classifies the possible interactions between various pollutants and material properties or functions under a given set of conditions, and is especially useful in visualizing the overall scope of the information-gathering problem.

The first major problem to be resolved in defining the effectivity matrix involves the designation of economically important materials.

Once the materials have been designated, their important properties and functions can be readily identified through analysis of usage patterns.

Then, after the important properties of economically important materials have been identified, the next obvious step is to determine which properties of the various materials are subject to either physical or chemical alteration by the different types of air pollutants.

By incorporating all of these factors in the effectivity matrix, the overall structure and scope of the study is defined: The possible interactions of the parameters encompass the essential effects of all identifiable pollutants on all economically important materials.

In the early stages of this project, it became evident that the pertinent data available on pollutant-material interactions were not sufficiently extensive or intensive to allow for differentiation according to specific material properties. Furthermore, the data seemed to indicate that in a polluted environment the majority of materials undergo a predominant failure mode, associated with the impairment of a primary function through alteration of one or more closely related properties.

Therefore, it was decided that the properties axis of the effectivity matrix should be eliminated. This was accomplished by assigning a predominant function to each material through an averaging process on the usage data available for that material.

The result was a matrix of much more manageable size, made up of pollutant-material pairs. The usage weighting factors for each material were to be used in computing several interaction multipliers for the evaluation of the economic significance of each matrix cell.

Selection of significant matrix cells: While the matrix classification is convenient, both for conceptualizing and for a computer storage and retrieval system, it must be recognized that not all cells are significant. For example, while O_3 is an important pollutant and concrete is an important material, their combination is trivial. Scientific and engineering judgment was applied to specify the significant matrix cells and to eliminate from further consideration those cells that have little economic importance.

It was relatively easy to classify many of the cells as significant or not significant. Some, however, were in a "gray" area and these areas (pollutant-material combinations) were therefore submitted to a review committee.

Completion of this task resulted in definition of the information gathering requirements.

Information collection plan: Having classified the possible interactions between various pollutants and materials in the effectivity matrix, it was possible to begin gathering information. An initial step was to develop an overall collection plan. This basic data collection plan enumerated the data requirements, developed data resource pairs, and estimated the effort required.

The task of enumerating the data required was a logical consequence of having previously identified the significant combinations of pollutants and materials as outlined above. These combinations were a result of the best scientific and engineering judgment available today and, as such, received the greatest attention in the analysis. For purposes of enumeration, however, all pollutant-material pairs were carried forward at this stage to avoid overlooking any economically significant interactions. It was recognized that data on a particular pollutant-material pair might not be available, in which case the pair might later become a candidate for proposed further research.

For each search task identified, an estimate of the effort necessary to obtain the information was made. This level of effort varies considerably from task to task; much of the information was obtained through personal contacts and telephone conversations.

MRI was particularly fortunate in having much of the required data available in its own technical library. Nearby Linda Hall Library of Science and Technology was also a valuable asset. The knowledge and expertise of the Institute's permanent technical staff and also of several consultants under contract to the Institute contributed significantly as a data source, particularly in the early phases of the study. Other organizations, such as NAPCA, were tapped for their information on air quality control.

Development of search strategies: Throughout the information gathering phase of this study a paramount concern was to devise search strategies that would maximize the time effectiveness of the information gathering tasks.

Information Gathering

Computerized searches: Ideally, all information concerning pollutant-material relationships should be found in computer data banks such as that found at NAPCA. The problem of searching for data would then be reduced to devising an algorithm for scanning these data banks. Unfortunately, little useful information was available in machine processible form. This was not unexpected, however, and caused no undue hardship or delay in the project's progress.

Literature search: The literature search was performed in three stages. The first stage consisted of a rapid search of readily available literature such as that on file at APTIC. This file provided an early overview of published literature along with contacts and references to other material. The second stage consisted of a search of literature in other disciplines such as materials research publications and other information sources not directly related to air pollution. The third stage included a more extensive search of literature that was not covered in the first two stages but that was essential to the project. Information not obtainable in any of these three stages became obvious by its omission and later constituted an important consideration in research and development planning.

Personal, mail, and telephone interviews: The literature search provided contacts such as the names of principal investigators of materials or pollution publications. Information not obtained from the literature and that could possibly be obtained from the principal investigator was pursued by contacting the investigator in person, by telephone, or by mail. The contact method depended on the relative importance of the questions to be answered.

Analysis

Analysis of data: This task was performed at the same time as the data gathering task. The objectives were: (1) continuous evaluation of matrix satisfaction; (2) assessment of quantity and quality of data gathered; (3) preliminary hypotheses on dosage-response relationships; and (4) establishment of the more significant economic effects.

Outputs of this task included requests for additional information.

Identification of information gaps: Rejection of certain effect matrix cells selected earlier was quite obvious. Many others, however, could be eliminated only after consultation with personnel who have had recent contact with research and development efforts in stress corrosion and other atmospheric effects. Others, of course, remained unresolved, representing technology gaps to be filled by further research.

This project did not attempt to fill such technological gaps, but did identify the major gaps and recommend approaches to that end where possible.

Analysis and ranking of technological gaps for future research: After elimination of obvious nonpertinent cells, the remaining cells were classified in terms of their economic importance based on prevalence of use of the material in the specified environment. This classification provided a scale of importance according to which each material-pollutant combination was reviewed by the technical review committee, who appraised the magnitude of the effect or indicated the lack of basis for such appraisal. The appraised magnitude of the effect and the economic importance rank were combined to produce a significance factor for each cell treated.

When the above ranking was complete, there remained a set of cells with a high economic rank, but which lacked technical bases for further treatment. These cells were evaluated in terms of the effort that appeared necessary to provide the desired decision base. This evaluation was, of course, subjective, but was carried out by a technical committee with extensive experience in the effects of atmosphere on physical properties. The factors of economic rank and technical effort required for decision were combined to provide a ranking of technological gaps as candidates for future research.

Definition of the dosage-response relationships: The dosage-response relationship can be expressed in terms of the damage incurred by a material exposed to a pollutant under specified conditions. The effect of a given pollutant on a specific property of a material is dependent upon three variable factors:

1. The concentration of the pollutant present in the atmosphere.

2. The time period over which the exposure occurs.

3. The other environmental conditions under which the exposure took place.

4. An effective surface/volume ratio for the exposed material.

Only laboratory experiments can produce the controlled environment necessary to provide complete information. A limited number of field studies, however, have been conducted in "measured" environments, and such studies fit into the analysis equally well. In this way, the degree of compatibility between laboratory investigations and field observations--and, consequently, some indication of the relative merits of laboratory work in future research programs--became apparent.

Objective measurement of damage effects presented some difficulties, especially when dealing with the aesthetic properties of materials. Whenever the damage could not be measured in quantitative terms, other measurements were devised.

Characterization of economic effects: Economic losses to materials can be attributed either to damaged properties or to impaired serviceability.

Economic evaluation of the effect of air pollutants on materials required that information from the preceding step--concerned with the dosage-response relationship--be translated into economic terms. The basic problem was to determine the extent of economic damage associated with a given level of physical or functional damage.

This problem was approached in different ways, depending upon the material and its application. In some cases, a "percent-condition" approach was adequate, with economic damage considered to be incurred at the same rate as the physical damage. Replacement of damaged materials was also included in this category, with replacement presumably occurring at the 100 percent damage (or zero percent condition) level.

In other cases, a cost-of-prevention or cost-of-restoration basis proved more suitable. Dirty windows and soiled clothing were typical of the restoration-cost category, with air pollution damage measured in terms of cleaning costs.

Documentation

Preparation of bibliography and list of organizations and personnel engaged in pollutant research: A bibliography of the pertinent literature and a list of the organizations or persons carrying out significant studies in this field were prepared following the analysis of the data. The bibliography and the list provide a starting point should it be felt necessary to carry out more extensive studies in this field or to review, in the light of further technological advances, the conclusions made at this time.

Preparation of final report: All the efforts described above have led to this final report. This report describes the weighted effect matrix, presents charts ranking the various matrix cells, and identifies the technological gaps for which future research is recommended.

In summary, the purpose of this report is to provide guidelines for the production of pollution criteria and materials selection criteria, and to identify areas for future research.

CHAPTER II

THE APPROACH TO ECONOMIC EFFECTS DETERMINATION

MATERIAL DETERIORATION

Air pollution damages materials by essentially two mechanisms: deterioration and soiling. When a material deteriorates, its economic value depreciates, and in some cases the material or product no longer performs its intended function. To determine the rate of economic loss from material deterioration one must know (1) the economic value of the material and (2) the rate of deterioration expressed as a percentage of the economic value lost per year. The rate of economic loss due to air pollution is determined by multiplying the economic value of a material exposed to air pollution by the difference between the rate of material deterioration in an unpolluted rural environment and the rate of deterioration in a polluted industrial or urban environment.

The calculation of economic loss may be further refined to identify the economic loss caused by a specific pollutant (material-pollutant combination) by performing a similar calculation except the rate of deterioration is associated with a given pollutant rather than with pollutants in general.

The economic value of material exposed to air pollution (Q) is calculated as the product of the annual dollar production volume (P), times a weighted average economic life of the material based on usage (N), times a weighted average factor for the percentage of the material that is exposed to air pollution (F). The calculation is expressed by the following equation:

$$Q = P \times N \times F$$

By further including a labor factor (R) to reflect the in-place or as-used value of the material, the equation becomes:

$$Q = P \times N \times F \times R$$

The economic value of material exposed to air pollution (Q) is in units of dollars of material exposed to air pollution.

Economic loss from material deterioration will indicate susceptibility to economic loss or potential loss; the results should not be interpreted as actually incurred economic loss.

Several important factors are not included in the estimate of value of materials exposed to pollution damage because the data are not available. The economic production data in the study reflect the final product values rather than material values. The economic data do not reflect a value of the service provided by the product. "Value of Service" is a vague term and very difficult to measure; however, it should not be ignored. For example, switching contacts in a computer are made of a silver alloy. If a contact becomes inoperative due to air pollution and the computer fails, the value of economic loss is larger than the cost of the switching contact. While this cost is real and probably important, no data are available to measure the magnitude of this type of second-order cost of material loss.

The rate of economic loss (L) is calculated as the product of the economic value of material exposed to air pollution (Q) times a value of interaction (V). The value of interaction is calculated by estimating the difference between the rate of material deterioration in a polluted environment compared to an unpolluted environment. The interaction value (V) is expressed as dollars lost per year.

MATERIAL SOILING

Calculation of the value of economic loss from material soiling is similar to calculation of economic loss from material deterioration. To calculate the economic loss due to material soiling, one must know the increased frequency of cleaning in a rural unpolluted environment over that in an industrial or urban polluted environment, and the cost of cleaning per dollar value of the material. Several approaches could be taken to obtain this information: (1) survey consumers to determine the amount spent; (2) survey the cleaning industry to determine the volume of business attributed to air pollution; and (3) assign an economic value to the loss in aesthetic beauty of a material caused by soiling. This study uses the third method.

DATA LIMITATIONS

Given the limitations of the available data, the value of economic loss was computed for the general category "pollutants." Data were available to examine the economic value of material loss for six materials: (1) stainless steel; (2) zinc; (3) building stone; (4) leather and paper;

(5) cotton; and (6) paint. However, gaps in the available data made it impossible to calculate with any precision the value of economic loss for other material-pollutant combinations.

While knowing the shortcomings in the available data, we feel it makes little sense to invest substantially in more sophisticated calculations at this time. Indeed, there can be no assurance that more sophisticated techniques would yield better results. If more extensive data were available, we would like to impose regional and perhaps local variations on the calculations, or to consider more extensive use of subcomponents of the variables, as well as to introduce checks to insure consistency among the various sets of calculations. In a certain gross and intuitive way, we did try to do this. But since there is no practicable way to determine the real value of economic loss due to air pollution, our methodology has several advantages: (1) it makes use of available data; (2) the results are consistent with intuitive judgment; and (3) it may be a reasonably good approximation of reality.

CHAPTER III

DATA COLLECTION PLAN

The data collection plan focused on the effects of air pollution on materials. The plan included a thorough search of the literature and interviews with individuals who have either published literature or conducted research in this field.

REVIEW OF THE LITERATURE

Members of the MRI project team reviewed several thousand articles, abstracts, manuals, proceedings, and reference books; of these, some 300 pieces of literature were selected for a project library. Literature selected for the library was classified according to (1) material, (2) pollutant, (3) article judgment, and (4) whether the article contained qualitative information concerning dosage-response relationships, pollutant concentration, time of exposure, or experiments within a controlled environment. An elementary information retrieval system on McBee Keysort cards was developed from this classification scheme; a detailed discussion of this information retrieval system is presented later in this chapter.

The following libraries, reference books, and journals provided the major portion of the literature.

San Francisco Bay Area Air Pollution Control District

The library at the San Francisco Bay Area Air Pollution Control District is complete, up to date, and provides easy access to the literature. Their microfilm library has 15,000 articles and abstracts. During the review of this microfilm library, which was purchased by MRI, 75 articles were selected for the project library. Most of these articles consisted of older literature and unpublished reports not available elsewhere.

Los Angeles Air Pollution Control District

The library at the Los Angeles APCD is not organized in a manner which allows easy access to their literature by outside researchers. The main function of this library is to circulate journals among their staff. No literature was obtained from this library.

American Society for Testing Materials (ASTM)

The special technical publications from the ASTM have useful information pertaining to the effects of air pollution on materials. One good reference is publication STP No. 435, Atmospheric Corrosion of Metals.

The ASTM has been testing the corrosion of materials in polluted and nonpolluted atmospheres for 50 years and has accumulated a great deal of data on corrosion rates. In almost all cases, however, their tests have simply been in rural, marine, urban, and industrial areas, with little attention to the specific pollutants responsible for the corrosion. The approach of the ASTM and the majority of work done in studying the corrosivity of a polluted atmosphere has been a pragmatic engineering approach to find an alloy or compound that withstands a severe industrial atmosphere.

Air Pollution Technical Information Center (APTIC)

The Air Pollution Technical Information Center, located in Raleigh, North Carolina, is up to date, and provides easy access to the literature. The APTIC library has a library of books and bound periodicals; a library of National Air Pollution Control Agency (NAPCA) publications and preprints; and a periodical library which includes more than 12,000 articles, reports, and abstracts on microfilm and index cards. Approximately 500 articles can be found in the APTIC microfilm library under key words effects, or materials. Sixty of these articles were included in this project's library. Another 40 articles were selected from the NAPCA publications and preprints for the project's library.

Articles were also obtained by searching through Chemical Abstracts. The key words searched were air pollution, atmosphere, building materials, corrosion, degradation, deterioration, ozone, paint, paper, and pollution. This search provided about 50 articles for the project library.

There are two reference books which contain excellent bibliographic references. Stern's Volume I, Air Pollution, Chapter 15 on the "Effects of Materials and the Economy," listed 137 sources of information, including proceedings, manuals, books, abstracts, and journals, which are now included in the project library. The reference book by Public Health Services (1969), Air Quality Criteria, Volume III, Chapter 4, "Effects of SO_2 on Materials," provided another 50 articles for the project library.

The 7th Decennial (Law) Digest, which covers the period 1956 to 1966, was reviewed for legal cases concerning material or property damage caused by air pollution. This subject is found under the heading NUISANCE, specifically NUIS 3 (3), 5 (2), and 6. In these 10 years only 15 cases are listed, with damages awarded in only 10 of these, with a total value of less than $25,000. Due to the paucity of information, the search of Law Digests was discontinued.

PERSONAL AND TELEPHONE INTERVIEWS

Several personal and telephone interviews were made to individuals who have either published articles or performed research on the effect of air pollution on materials.

MRI requested from the Science Information Exchange, Smithsonian Institution, Washington, D. C., a list of current projects involved with economic effects of air pollution on materials and effects of air pollution on materials. The Science Information Exchange currently registers 100,000 one-page records of research annually. Most of the names of people contacted, personally or by telephone,came from the Science Information Exchange.

Visits included trips to the San Francisco Bay Area and the Los Angeles Air Pollution Control District Headquarters, the National Bureau of Standards Division of Building Materials, and the Philadelphia and Pittsburgh areas.

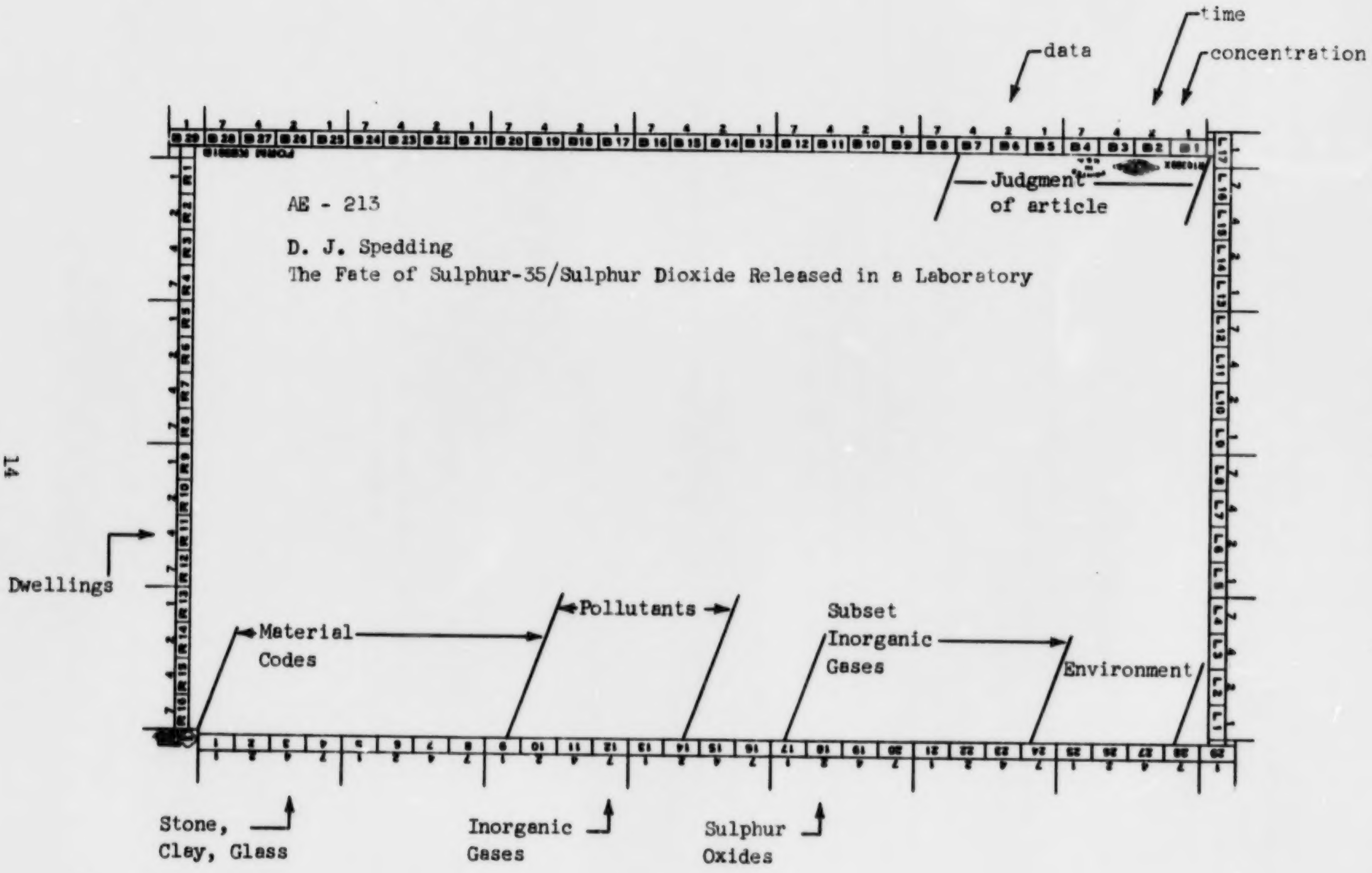
INFORMATION CATALOGING AND RETRIEVAL

The project bibliography consisted of more than 300 articles, reviews, and reports that were selected after a review and analysis of several thousand documents. Appendices B and C contain a bibliography of the literature reviewed for this project.

All articles contained in the MRI effects of air pollution on materials library were coded on McBee Keysort cards. An example of a typical McBee Keysort card is shown in Figure 1. The selection code is grouped into four major classes: (1) material, (2) pollutant, (3) article judgment, and (4) quantitative information. Each major class is composed of sets and subsets, as described below.

Material

Under the major class "Material" are nine sets, coded 1 through 9, as follows:



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D. J. Spedding
The Fate of Sulphur-35/Sulphur Dioxide Released in a Laboratory

time
data
concentration
Judgment of article
Dwellings
Material Codes
Pollutants
Subset Inorganic Gases
Environment
Stone, Clay, Glass
Inorganic Gases
Sulphur Oxides

Example of McBee Keysort Card

Figure 1

Set	Code
Ferrous metals	1
Nonferrous metals	2
Stone, clay, glass	3
Plastics and rubber	4
Fibers	5
Finishes and coatings	6
Other materials	7
General	8
Economic	9

The first seven sets are those described in Chapter VI, Economically Important Materials. When a material was discussed in an article, the appropriate code number was notched in the McBee Keysort card. An article that treated air pollution damage in a general manner, without serious reference to a particular material was coded "8". An article that was an economic study was coded "9". Each set of materials could also be further coded by use of the R value on the Keysort Code. The R subsets specify particular materials as shown in Table I.

An example of how the McBee Keysort cards were used in this study is given below:

Example: Find all articles dealing with the effects of air pollution on lead. Run a sorting rod through the code 2 holes for the set of all nonferrous metals. All cards having to do with nonferrous metals are notched in the number 2 hole and will be left behind. Next run the rod through the holes R-8 for lead; all cards for articles concerned with lead will be left. Notice that this method of coding does not result in a completely unambiguous answer. Suppose in the above search for articles on lead, an article had discussed aluminum and glass. This article would show up with the collection of articles on lead because code 2 and R-8 are notched, code 2 for aluminum and R-8 for glass. This occasional ambiguity only rarely causes conflict because the title of the article will in general easily distinguish between questionable cases.

TABLE I

SETS AND SUBSETS OF MATERIALS FOR McBEE KEYSORT INDEX

Ferrous Metals

1 Gray iron
2 Malleable iron
3 Alloy steel
4 Carbon steel
5 Stainless steel

Nonferrous Metals

1 Aluminum
2 Brass and bronze
3 Chromium
4 Copper
5 Gold
6 Magnesium
7 Molybdenum
8 Lead
9 Nickel
10 Silver
11 Tin
12 Zinc

Stone, Clay, Glass

1 Building stone
2 Building brick
3 Clay pipe
4 Cement and concrete
5 Abrasives
6 Refractory ceramics
7 Nonrefractory ceramics
8 Glass
9 Carbon and graphite
10 Mica
11 Dwellings

Plastics and Rubber

1 Synthetic rubber
2 Natural rubber
3 Polyethylene
4 PVC
5 Polystyrene
6 Phenolics
7 Polypropylene
8 Urea and melamine
9 Polyesters
10 ABS
11 Acrylics
12 Cellulosics
13 Epoxies
14 Acetate
15 Nylons

Fibers

1 Cotton
2 Wool
3 Rayon
4 Acetate
5 Acrylics
6 Polyester
7 Nylon
8 Polyolefins
9 Cellulose esters
10 Fabrics

Finishes and Coatings

1 Paint
2 Dyes

Other Materials

1 Wood
2 Paper
3 Leather
4 Bituminous materials
5 Computers

General

Economic

NOTE: The number preceding each material identifies the R value of the subset.

Pollutant

If possible, the pollutant was identified as belonging to one of the following major sets:

Set	Code
Organic gases	11
Inorganic gases	12
Solid particulate	13
Liquid particulate	14
General	15

These inorganic gases which were specifically identified were further listed in the following subset:

Subset of Inorganic Gases	Code
NOX	17
SOX	18
COX	19
NH_3	20
HCl	21
HF	22
H_2S	23
O_3	24

Due to a lack of literature, the other major sets were not further subdivided.

Any cause of deterioration, corrosion, or damage assignable to biological, radiation, "natural" weathering, etc., was coded under "General"--code 15.

When tests were performed in environments in which the type of pollutant responsible for the effect was unknown, but the location was well established, the articles were coded in the following sets:

Set	Code
Rural	25
Urban	26
Industrial	27
Marine	28

It was possible that an article was concerned with industrial exposure tests but also correlated the results to the SO_2 concentration present. This article would be notched at holes 27, 18, and 12.

Article Judgment

After reading each article, value judgments were made regarding the content of each. Location exposure tests in which only the time of the exposure were noted are coded under Time. If some correlation of the level of pollutant causing or suspected of causing the effect is attempted, this was noted under Concentration. Only laboratory experiments under well controlled conditions were coded under Controlled Environment. Articles were also judged as review articles and whether or not data were presented. When it was doubtful whether the article was of useful value to the project, it was notched under Doubtful Value. Articles of only the slightest value did not receive the Doubtful Value notch. These article judgments were coded under the B values on the Keysort cards with the following code:

Judgment	B Value
Concentration	1
Time	2
Controlled Environment	3
Review	5
Data	6
Doubtful Value	7

CHAPTER IV

INTENSITY OF AIR POLLUTION

REPRESENTATIVE CONCENTRATIONS

In applying experimentally determined dosage-response relationships for damage to materials by air pollutants, or in deriving such relationships from experimental data, it is necessary to know the concentrations of the pollutants involved in the particular region of space-time occupied by the material being considered. Pollutant concentrations vary in space and time as a result of variations in the location of pollutant sources, time dependence on their activity, continually changing climatic factors, and transient distributions of chemical reactions in the atmosphere.

Patterns of concentration variation are peculiar to each locality but show distinctive features for certain parts of the country if only in the predominance of particular pollutants. For example, metropolitan areas on the West Coast are characterized by high concentrations of ozone and nitrogen oxides, while on the East Coast high concentrations of sulfur dioxide and particulate matter are the rule.

What little data are available on pollutant damage to materials are usually given (for example in the ASTM studies) in terms of either a rural or an urban (residential, commercial, or industrial) environment. Fortunately, data on pollutant concentrations from the National Air Surveillance Networks are presented in the same fashion--according to location of the sampling stations. In view of these facts, it seemed worthwhile as part of this project to develop a list of representative urban and rural values for the concentrations of the major air pollutants. The results of this effort are presented in Tables II and III. The pollutant classification scheme presented in these tables, a modification of that adopted by the Los Angeles Air Pollution Control District, emphasizes those pollutants to which most of the material damage can be attributed.

Several of the values (as indicated in the tables) are annual averages of data from NASN. These values are the most broadly based and best meet the desirable criteria for the purposes in mind. The rest of the data were taken from a variety of studies of a much smaller scale, as reported in the literature. These latter values are suspect due to the lack of similarity in sampling times and in the location and design of the air sampling devices used. For example, markedly different results can be obtained at a given location from samples taken at ground level and those taken on top of a 50-ft. building. In spite of these difficulties, the situation is improved by the fact that materials subject to attack are widely distributed and deteriorate over long periods of time.

TABLE II

SIGNIFICANT POLLUTANTS AND TYPICAL CONCENTRATIONS-- GASEOUS POLLUTANT PREVALENCY

(Typical concentrations in parts per million by volume)

Code	Pollutant	Urban	Rural
100	Organic Gases	3.0*	1.0
110	Hydrocarbons (90% CH_4)	2.8	1.0
120	Others	0.2	0.05
121	Total aldehydes	0.05	0.01
200	Inorganic Gases		
210	Oxides of nitrogen		
211	Nitric oxide	0.05*	0.01
212	Nitrogen dioxide	0.05*	0.02
220	Oxides of sulfur		
221	Sulfur dioxide	0.05*	0.005
222	Sulfur trioxide	<0.001	<0.001
230	Oxides of carbon		
231	Carbon monoxide	7.0*	0.1
232	Carbon dioxide	350	315
240	Others		
241	Ammonia	0.1	0.01
242	Hydrogen chloride	0.05	0.005
243	Hydrogen fluoride	0.01	0.003
244	Hydrogen sulfide	0.003	<0.001
245	Ozone	0.05*	0.02

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* From National Air Surveillance Networks.

TABLE III

SIGNIFICANT POLLUTANTS AND TYPICAL CONCENTRATIONS--PARTICULATE POLLUTANT PREVALENCY

(Typical concentrations in $\mu g/m^3$)

Code	Pollutant		Urban[a]
	Total Particulates		120[b]
300	**Solid Particles**		110
310	Carbon/soot particles		
311	combustible fraction		
312	non-combustible fraction	}	75
320	Metal oxides and salts	}	
330	Silicates and mineral dusts		10
340	Miscellaneous organic particles		
		311 + 340	25
400	**Liquid Particles**		10
	For Total Particulates[c],		
	Chloride content		4
	Nitrate content		4*
	Phosphate content		1
	Sulfate content		13*
	Aluminum content		5
	Calcium content		4
	Iron content		3*
	Ammonium content		0.7*
	Lead content		1*
	Silicon content		4
	Zinc content		0.5*

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* From National Air Surveillance Networks

[a] Rural values are approximately 30% of the urban values.

[b] Based on the NASN average for suspended particulates of 100 $\mu g/m^3$ and a dustfall value of 300 tons/mi^2-month.

[c] Fifteen other elements are known to be present at lower concentration levels.

CONTRIBUTION OF DUST PARTICLES

Dustfall refers to settled particulate matter in the size range greater than 10 microns (μ). By size is meant the equivalent aerodynamic diameter; that is, the diameter of a sphere of unit density ($1\ gm/cm^3$) having the same settling velocity as the particle in question. The size of a dust particle is roughly equivalent to the largest length dimension of the particle. The effect of non-sphericity of dust particles tends to be offset by particle densities averaging considerably above the unit value.

Due to the pronounced settling tendency of dust particles, dustfall rather than dust particle concentration is reported as a measure of air pollution. On the other hand, suspended particulate pollution, which includes small dust particles, is reported in units of concentration. These differences in measurement techniques make it difficult to determine the total particulate pollution level.

Since high-volume samplers used in the NASN program collect particles up to 100 μ in size,[1] there is considerable overlap with dustfall measurements. The extent of this overlap depends on the size distribution of particulate matter. Although such data are available for the fraction of particles less than 10 μ, little has been reported for dust particles.

Fairweather, Sidlow, and Faith[2] have measured size distributions for dustfall at rather highly polluted industrial sites and have found 90 percent of the weight in the fraction of dust particles greater than 40 μ with a mass median size of about 100 μ. Using a high volume sampler, Shanty and Hemeon[1] have reported about 35 percent of the total sample weight to be associated with the 10-100 μ range. (See Table III.) Total suspended particulates were measured at levels slightly above the NASN urban average of about 100 $\mu g/m^3$.[3]

The concentration of airborne dust particles may be approximated by

$$C = \frac{J}{V}$$

where J is the dustfall and V the settling velocity associated with the area mean size of dust particles. Typical values for J are 30 $tons/mi^2$-month or 1.0 mg/cm^2-month.[4]

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1. F. Shanty and W. C. L. Hemeon, J. APCA, 13, 211 (1963).
2. J. H. Fairweather, A. F. Sidlow and W. L. Faith, J. APCA, 15, 345 (1965).
3. "Air Quality Data," NAPCA Publication No. APTD 68-9 (1968).
4. "Air Quality Criteria for Particulate Matter," NAPCA Publication No. AP-49 (1969).

If the area mean size for dust particles is taken to be 50 μ with a settling velocity of 7 cm/sec,[4] the dust particle concentration from the above equation is about 55 μg/m^3. This places the level of total particulate pollution at 120 μg/m^3.

CHAPTER V

PHYSICAL/CHEMICAL EFFECTS OF AIR POLLUTANTS ON MATERIALS

Air pollutants may attack materials in a variety of ways, inflicting damage ranging from reversible soiling to irreversible chemical alteration. The general damage mechanisms have been recently outlined by Yocum and McCaldin.1/ In the literature, the corrosion of metals has received the most attention. Very little study has been reported on the mechanisms of chemical attack on polymeric materials, particularly plastics. Table IV summarizes our opinion of the chemical resistance of materials to air pollutants.

Many factors other than the nature of pollutants themselves influence the rate of attack on materials. Of these factors, moisture is the most important. Moisture in the form of humidity is a requirement for chemical attack; above certain levels moisture may substantially accelerate the rate of attack. These critical humidity values are well known for the corrosion of specific metals.

EFFECTS OF ORGANIC GASES, INORGANIC GASES, AND PARTICULATE POLLUTION

Organic Gases

Very little information is available on the damage potential of organic gases. Reactivities are generally thought to be insignificant. The major exception occurs in the case of certain polymeric materials, as indicated in Table IV.

Inorganic Gases

Inorganic gases exhibit the greatest potency for chemical attack on materials. Table V summarizes the chemical and physical (property) manifestations of the most severe interactions between inorganic pollutant gases and receptor materials. (These interactions are rated "P" in Table IV.) As used in the table, the term "corrosion" implies, in addition to loss of material, formation of a surface film which usually has an aesthetically undesirable apperance.

1/ See Air Pollution, Vol. I, Chapter 15. Edited by A. C. Stern, Academic Press, New York, 1968.

TABLE IV

CHEMICAL RESISTANCE OF MATERIALS TO POLLUTANTS

	Pollutant					
Material	Organic	NO_x	SO_x	O_3	CO_x, NH_3, HCl, H_2S	Particulate
100.0 Ferrous						
101.0 Gray iron	F	E	P	E	F	P
102.0 Malleable iron	G	E	F	E	F	F
103.0 Alloy steel	G	E	P	E	P	P
104.0 Carbon steel	G	E	P	E	P	P
105.0 Stainless steel	E	E	E	-	F	F
200.0 Nonferrous						
201.0 Aluminum	G	E	F	E	G	G
202.0 Brass and bronze	E	E	F	E	P	P
203.0 Chromium	E	E	G	E	G	G
204.0 Copper	G	E	P	E	P	P
205.0 Gold	E	E	E	E	G	G
206.0 Magnesium	G	E	F	E	G	G
207.0 Molybdenum	E	E	G	E	G	G
208.0 Lead	G	E	E	E	G	F
209.0 Nickel	E	E	F	E	F	E
211.0 Tin	E	E	P	E	F	F
210.0 Silver	E	E	P	E	F	F
212.0 Zinc	F	E	P	E	F	P
300.0 Stone, clay, glass						
301.0 Building stone	G	E	P	E	G	F
303.0 Building brick	G	E	G	E	G	F
306.0 Cement and concrete	G	E	P	E	G	G
309.0 Nonrefractory ceramics	-	-	-	-	-	-
310.0 Glass	E	E	E	E	G	E
312.0 Carbon and graphite	E	E	E	E	E	E
400.0 Plastic and rubber	-	-	-	-	-	-
470.0 Synthetic rubber	P	G	G	G	E	P
401.0 Natural rubber	P	G	F	P	E	P
421.0 Polyethylene	G	G	G	F	E	G
425.0 Polystyrene	P	E	E	F	E	P
426.0 PVC	P	G	E	G	E	P
431.0 Phenolics	F	G	E	G	E	P
422.0 Polypropylene	G	G	E	F	E	F
432.0 Urea and melamine	E	G	G	G	E	P

TABLE IV (Concluded)

433.0 Polyesters	F	G	G	G	E	P
428.0 Acrylics	P	G	G	G	E	P
441.0 ABS	F	G	P	G	E	P
429.0 Cellulosics	F	G	G	G	G	P
451.0 Epoxies	E	G	E	G	E	P
461.0 Acetate	G	G	F	F	F	P
423.0 Nylons	G	G	P	F	F	G
500.0 Fibers						
501.0 Cotton	G	G	P	F	F	P
511.0 Wool	E	G	F	G	E	F
521.0 Rayon	F	G	P	P	F	P
542.0 Acetate	P	G	P	G	G	P
543.0 Acrylics	P	G	E	G	E	P
531.0 Nylons	G	F	P	P	G	P
544.0 Polyester	P	G	G	G	G	P
546.0 Polyolefins	P	F	E	F	G	P
541.0 Cellulose esters						
600.0 Finishes and coatings						
601.0 Paint	G	G	F	F	P	P
700.0 Other materials						
701.0 Wood	G	G	F	F	F	F
711.0 Paper	G	E	P	G	G	F
721.0 Leather	G	G	P	G	G	F
731.0 Bituminous materials	G	G	E	G	G	G

E = excellent
G = good
F = fair
P = poor

TABLE V

CHEMICAL ATTACK BY INORGANIC POLLUTANT GASES

Pollutant	Material	Chemical Manifestation	Physical Manifestation
SO_x	100 Ferrous metals	Increased formation of rust (hydrated ferric oxide) containing sulfate	Corrosion
	204 Copper	Formation of basic copper sulfate soluble in acid	Corrosion
	212 Zinc	Formation of basic zinc sulfate, soluble in acid	Corrosion
	301 Building stone	Conversion of carbonates to soluble sulfates involving volume increase	Loss of cohesion, flaking
	306 Cement and concrete	Conversion of carbonates to soluble sulfates involving volume increase	Loss of cohesion, flaking
	423 Nylon		Cracking, embrittlement
	441 ABS		Cracking, embrittlement
	501 Cotton	Acid hydrolysis of cellulose, lowering degree of polymerization	Reduced tensile strength
	521 Rayon	Acid hydrolysis of cellulose, lowering degree of polymerization	Reduced tensile strength
	531 Nylon		Reduced tensile strength
	542 Acetate		Reduced tensile strength
	711 Paper	Formation of sulfuric acid within material	Embrittlement, discoloration
	721 Leather	Formation of sulfuric acid within material	Reduced tensile strength
O_3	401 Natural rubber*	Breaks carbon/carbon double bond resulting in chain scission	Severe cracking, lowered resiliency
	521 Rayon		Reduced tensile strength
	531 Nylon		Reduced tensile strength
NH_3	202 Brass and bronze*	Attacks grain boundaries	Corrosion cracking
HCl	100 Ferrous metals	Promotes electrochemical attack	Corrosion
H_2S	103 Alloy steel*	Attacks grain boundaries	Corrosion cracking
	104 Carbon steel*	Attacks grain boundaries	Corrosion cracking
	204 Copper	Formation of sulfide film	Increase of electrical contact resistance, discoloration
	601 Paint	Formation of heavy metal sulfides	Darkening

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* Stressed.

Particulate Pollution

The most noticeable damage to materials by particulate matter is soiling. Although there may be no chemical interaction with the material, this process is seldom completely reversible because mechanical removal of the deposited matter usually results in some erosion of the surface of the material.

Deposited particulate matter may also damage materials by direct chemical action. Oily and tarry particles, which adhere particularly well to surfaces, are normally acidic and cause slow but persistent deterioration of the substrate material.

Nearly two-thirds of particulate matter is made up of a combination of carbon and soot particles and metal oxides and salts. These substances greatly enhance the damage potential of the pollutant gases. Many of the salts are hygroscopic and act as corrosion nuclei on metals; they may also catalyze the corrosion reactions. Carbonaceous particles, on the other hand, not only serve as condensation nuclei, but are probably responsible for the conversion of absorbed gases to the corresponding oxidized acids. This process is thought to occur with sulfur dioxide, which is transformed to highly reactive sulfuric acid, under the catalytic action of traces of metals, especially iron (AE-113).*

DOSAGE-RESPONSE RELATIONSHIPS

The useful lifetime of a material is that period over which the properties of the material remain within acceptable limits according to its use. For materials that are exposed to the atmosphere, the properties affected may be mechanical, electrical, thermal, or aesthetic.

In the absence of air pollution, the useful life expectance, T, of a material depends on several factors, as expressed in the following functional relationship

$$T = f\,(F_1 \cdots F_n,\ R_1 \cdots R_m,\ A_{eff}/V) \qquad (1)$$

In this equation F_n represents intensities of climatic factors, such as temperature, relative humidity, wind speed, and concentrations of naturally occurring atmospheric chemical species, both gaseous and particulate. The R_m represents reactivity factors which reflect the degree of response of the material to base levels of climatic factors, either alone or in combination. The inclusion of the ratio A_{eff}/V accounts for the fact that materials deteriorate largely by surface mechanisms; A_{eff} is the initial effective exposed surface area of the material and V is its volume.

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* AE numbers listed throughout the text refer to the Accession Bibliography (Appendix C).

A brief discussion of the use of the effective surface area is in order. Deterioration by a surface mechanism depends on the movement of damaging agents to the surface of the material (and often on the movement of reaction product away from the damaged surface as well). In the case of a nonporous material, pollutant is rapidly transported to all of the exposed surface by convective air currents. In the case of a porous material, such as a woven fabric, however, movements to partially protected surface elements occurs by a much slower diffusive mechanism. The effective surface area of a woven fabric, for example, is only a small fraction of the actual fiber surface area. (This fact supports the truncated thickness value that has been assigned to fibrous materials.)

The rate of deterioration of a material is simply the inverse of its life expectancy. Air pollution decreases the economic value of a material by increasing its natural rate of deterioration, which results in a reduced economic lifetime. The reduced lifetime, T^* , is a function of the variables contained in Equation (1) as well as of a set of concentrations of reactive air pollutants and a set of additional reactivity factors that reflect the effects of specific pollutants, individually or in synergistic combination with other pollutants or with certain climatological factors.

The response of a material to air pollution, then, is reflected by a functional relationship similar to Equation (1):

$$\frac{1}{T^*} - \frac{1}{T} = g(F_1 \cdots F_n,\ R_1 \cdots R_n,\ A_{eff}/V) \qquad (2)$$

where the left side of this equation represents the increased rate of deterioration of the material.

Consider the case of a particular material of a specified size and shape that is damaged by a single pollutant. Assume further that the intensities of the influential climatological factors are held constant and, most important, that the response of the material is linearly dependent on the concentration of the damaging agent. For these conditions, Equation (2) simplifies to

$$\frac{1}{T^*} - \frac{1}{T} = KF \qquad (3)$$

Multiplying both sides of this equation by exposure time and integrating, produces

$$P = KD \qquad (4)$$

where P is the percentage reduction in economic lifetime and D is the pollutant "dosage," defined by

$$D = \int_{t_1}^{t_2} F\, dt = \bar{F}\Delta t \qquad (5)$$

Strictly speaking, then, the use of the concept of dosage implies a first-order dependence of the material response on the pollutant concentration. This dependence is likely for damage mechanisms limited by diffusion of the damaging agent to the receptor surface, as would be the case for soiling.

Equation (2) completely defines the response of a material exposed to any combination of air pollutants. Very few pollutant-material interactions have been studied to the extent that expressions of this type can be written. An isolated example of an attempt in this direction is presented in a case study on zinc.1/ Generally, information has been presented for a polluted versus an unpolluted environment. This approach masks understanding of the damage mechanisms and identification of the specific pollutants involved.

Consideration of the likely complexity of Equation (2) helps one to appreciate the difficulties that have been consistently encountered when relationships of that form were sought through accelerated testing. One is confronted with the problem of increasing in the same proportion all of the factors active in a particular mode of deterioration. Even then, results cannot be extrapolated to realistic exposure conditions unless the dependence on each active factor is of prescribed mathematical simplicity.

1/ See Appendix E.

CHAPTER VI

ECONOMIC VALUE OF MATERIALS EXPOSED TO AIR POLLUTION

One of the major tasks of this study is to determine the economic value of materials exposed to air pollution. This task was accomplished in the following manner:

(1) Identify the economically important materials on the basis of annual production dollars;

(2) Determine an estimate of the composite economic life for each material;

(3) Estimate the labor content factor for computing in-place material values; and

(4) Estimate the percent of the material exposed and unprotected from air pollution.

The economic value of materials exposed to air pollution is the product of these four terms.

ECONOMICALLY IMPORTANT MATERIALS

There are more than 12,000 commonly used materials, all of which can be said to have some economic value. These materials range in actual cost from less than $10 per ton (concrete, for example) to more than $1,000 per pound (platinum, iridium, and rhodium). The economic importance of a material is a function of several factors, including its unit value, extent of use, and applications.

Defined in these terms, only about 500 materials can be viewed as having real economic significance. Of the 500, the top 20 percent, or 100 materials, probably account for about 60 percent of the total value of all materials. About 75 materials represent 50 percent of the total value and 50 materials make up 40 percent. The 25 most important materials comprise 25 percent of the total value of the 500 materials.

The economic value of most materials is due to a relatively few important properties. These properties, in turn, are important only with reference to specific materials. Electrical conductivity, for example, is an important characteristic of copper wire, but is irrelevant with respect to concrete; weldability is important with structural steel, but meaningless with most other materials. Thus, it is important to identify the specific properties to which each economically important material owes its economic value. In all, more than 50 different quantitatively measurable properties of materials impart specific economic value to certain materials, in certain applications, under certain conditions. Table VI lists some of these important materials properties.

A list of 300 important materials was gathered from published sources. This list was reviewed by MRI personnel and additions were made on the basis of their experience. A number of economically important uses could be identified for all the listed materials.

Production and sales data were then obtained for all of the materials on the list. Whenever feasible, similar materials, such as "bituminous materials" or "refractory ceramics," were grouped together.

To condense the materials list to a manageable size, a cutoff point of about $50 million in the total U. S. annual production was arbitrarily set. The resulting list contained just over 50 materials or materials groups. These constitute the materials having the largest annual dollar volumes.

Some distinction is necessary between what is meant by "materials value" and "product value" and how these values are interpreted and used.

Synthetic rubber is a good example. While only a billion dollars worth of rubber is consumed yearly, the value of rubber products consumed exceeds $8 billion annually. And it is the rubber product, not simply the rubber material, that is subjected to damage through exposure to air pollutants. Damage, then, must be considered to rubber products, such as tires, rather than to the rubber material.

The same is true of many of the other materials. The reported value of the various nonferrous metals is generally based on an intermediate stage of the material. Aluminum, for example, comes from the mill as ingots which will be further processed into sheet, castings, wire, and other forms. Similarly, tin is produced as bars or pigs, and zinc in slabs or blocks.

Some of the important ferrous metals--chiefly carbon steel--are reported on a different basis. Steel mill output is in the form of sheet, structural shapes, pipe and tubing, rods, and the like--essentially in a usable form that will be incorporated in some type of structure.

Most building materials are produced essentially as used--paint, brick, concrete block, building stone, glass, asphalt, and so forth. An additional element of value is added by installing the material in its ultimate end use; the value of material affected by air pollution is the in-place value.

TABLE VI

PROPERTIES OF MATERIALS

Mechanical Properties

- density
- tensile strength
- compressive strength
- shear strength
- impact strength
- creep strength
- fatigue strength
- hardness
- porosity
- gas permeability
- liquid absorptivity
- capillarity
- elastic moduli
- elastic limit
- resilience
- dimensional stability
- foldability
- wet collapse
- coefficient of friction
- adhesion strength

Electrical Properties

- volume resistivity
- surface resistivity
- magnetic permeability
- arc resistance

Thermal Properties

- conductivity
- heat capacity
- coefficient of expansion
- emissivity
- absorptivity
- flammability
- maximum service temperature

Aesthetic Properties

- color
- reflectivity
- transparency
- refractive index
- surface finish
- texture

The chief intermediate materials, then, include most of the nonferrous metals, rubbers and plastics, wood, and leather. Materials produced in final form include steel; most stone, clay, and glass items; coating materials; paper; and petroleum products.

The values of the intermediate materials have been modified to reflect the actual value of the exposed item, exclusive of its installation cost, by applying an adjustment factor to the basic material value. This adjustment factor varies widely among the different materials, but falls generally in the 2.0 to 8.0 range.

With these adjustments, the dollar production volumes should closely reflect the actual economic value of the various materials. These values are summarized in Table VII.

TOTAL ECONOMIC VALUE

Total economic value depends not only upon the amount of material placed in service during a year, but also on the labor content factor and the economic life of that material. The product of annual dollar volume, economic life, and labor content factor, gives a measure of the total value of a given material in use. Then, multiplying this quantity by the percentage of that material actually exposed to air pollution gives a relative measure of the total value of a material susceptible to damage by air pollutants.

Economic Life of Materials

To determine the overall economic life of a material, its uses must be identified and then the economic life of the material for each use considered. For example, aluminum used in construction has a useful life of 40 years or more, while aluminum used in beverage cans is consumed in less than a year. Similarly, lead used in battery plates has a much shorter economic life than lead used in pipe. Polystyrene used in electrical appliances lasts longer than polystyrene used as a packaging material. The useful life of material is based, whenever possible, on the depreciation guidelines and rules published by the United States Treasury Department, Internal Revenue Service. An estimate of the life of each major use for each material is made and a weighted average is taken to arrive at the composite life for a material. This estimate of the composite life represents an economic life rather than a physical life.

TABLE VII

ANNUAL PRODUCTION OF ECONOMICALLY IMPORTANT MATERIALS

Material	$ Production (billions)
Ferrous Metals	
Gray iron	3.216
Malleable iron	0.486
Alloy steel	2.160
Carbon steel	13.000
Stainless steel	1.000
Nonferrous Metals	
Aluminum	3.380
Brass and bronze	0.600
Chromium	0.113
Copper	2.041
Gold	0.124
Magnesium	0.590
Molybdenum	0.238
Lead	0.728
Nickel	0.646
Silver	0.105
Tin	0.506
Zinc	0.540
Stone, Clay, Glass	
Building stone	0.095
Building brick	0.375
Clay pipe	0.103
Cement and concrete	6.081
Refractory ceramics	0.700
Flat glass	0.592
Carbon and graphite	0.339
Finishes and Coatings	
Paint	2.587

Material	$ Production (billions)
Other Materials	
Wood	10.875
Paper	20.927
Leather	5.146
Bituminous materials	1.106
Plastics and Rubber	
Synthetic rubber	6.660
Natural rubber	1.790
Polyethylene	0.975
PVC	0.700
Polystyrene	0.850
Phenolics	0.366
Polypropylene	0.403
Urea and melamine	0.420
Polyesters	0.228
ABS	0.278
Acrylics	0.278
Cellulosics	0.228
Epoxies	0.147
Acetate	0.058
Nylons	0.106
Fibers	
Cotton	3.336
Wool	1.085
Rayon	0.288
Acetate	0.165
Acrylics	0.170
Polyesters	0.136
Nylon	0.830
Polyolefins	0.036
Cellulose esters	0.717

Labor Content Factors for Computing "In-Place" Material Values

Factors reflecting the in-place or as-used values of the various materials have also been developed. These factors are summarized in Table VIII.

The magnitude of the factors indicates the difference in value between the basic material as it is produced and its use in a finished product or structure. This value is defined as the ratio of the total in-place cost to the materials value reported in Table VII.

Multiplying the economic value of paint, for example, by the appropriate factor gives the total cost of paint applied to a surface; this figure, then, actually represents the dollars exposed to air pollutants.

The factors have been kept separate from the materials values to avoid confusion with the economic data compiled by the Department of Commerce, Bureau of Mines, and other reporting agencies.

These value adjustment factors have been weighted according to the different uses of each material. Thus, they are calculated on the same basis as the exposure indexes and economic lives, and can be used in conjunction with these other factors.

Exposure Index

The proportion of a material actually exposed to air pollution is another important factor in evaluating the overall importance of the various economically important materials with respect to their vulnerability to damage by air pollutants. Again, the extent to which a material is exposed to air pollution depends upon its uses. Lead used in batteries, for example, has relatively little exposure to air; but the lead used in paint pigments has a high exposure. Polystyrene used in signs is exposed to a far greater degree than polystyrene used as an insulating material. Steel and wood are seldom exposed unpainted or otherwise unprotected.

An assumption was made that the distribution of products is approximately the same as the population distribution. Based on this assumption, approximately 75 percent of all products are located in standard metropolitan statistical areas. Not all of these products are exposed out-of-doors where the interactions of climatological conditions and pollutants can affect materials. Estimates were made of the fraction of material which is protected from direct attack by air pollution. These correction factors ranged from 0.00 to 0.98.

TABLE VIII

LABOR CONTENT FACTORS FOR COMPUTING "IN-PLACE" MATERIAL VALUES

Material	Factor	Material	Factor
Ferrous Metals		Fibers	
Gray iron	2.0	Cotton	1.9
Malleable iron	2.0	Wool	1.9
Alloy steel	2.4	Rayon	1.9
Carbon steel	2.3	Acetate	1.9
Stainless steel	2.1	Acrylics	1.9
		Polyester	1.9
Nonferrous Metals		Nylon	1.9
		Polyolefins	1.9
Aluminum	2.0	Cellulose esters	1.9
Brass and bronze	2.3		
Chromium	2.4	Stone, Clay, Glass	
Copper	2.4		
Gold	2.0	Building stone	2.3
Magnesium	2.3	Building brick	2.3
Molybdenum	2.9	Clay pipe	2.8
Lead	2.0	Cement and concrete	2.6
Nickel	2.3		
Silver	3.0	Refractory ceramics	2.3
Tin	2.1		
Zinc	2.3	Flat glass	2.3
		Carbon and graphite	2.4
Plastic and Rubber			
		Finishes and Coatings	
Synthetic rubber	1.0		
Natural rubber	1.0	Paint	3.3
Polyethylene	1.0		
PVC	1.0	Other Materials	
Polystyrene	1.0		
Phenolics	1.0	Wood	1.8
Polypropylene	1.0	Paper	2.0
Urea and melamine	1.0	Leather	1.0
Polyesters	1.0	Bituminous material	2.9
ABS	1.0		
Acrylics	1.0		
Cellulosics	1.0		
Epoxies	1.0		
Acetate	1.0		
Nylons	1.0		

RESULTS

The results of the operations described in this chapter have been collected and are presented in Table IX. The materials have been ranked in decreasing order of economic value. In the absence of any valid material/pollutant interaction values, this ranking could serve to identify the relative economically significant materials with respect to expected damage due to air pollution.

If interaction values for material/pollutant combinations are available, the total dollar damage resulting from exposure of a given material to a specified pollutant concentration may be calculated from the values in Table IX.

TABLE IX

ECONOMIC VALUE OF MATERIALS EXPOSED TO AIR POLLUTION

Rank	Material	Annual Production (billion $)	Economic Life (year)	Exposure Index*	Labor Content Factor	In-Place Material Exposed to Air Pollution (billion $)
1	Cement and concrete	6.081	40	0.5	2.6	316.21
2	Copper	2.041	22	0.5	2.4	54.88
3	Aluminum	3.380	16	0.5	2.0	54.08
4	Brass and bronze	0.600	40	0.6	2.3	33.12
5	Flat glass	0.592	30	0.7	2.3	28.59
6	Zinc	0.540	36	0.6	2.3	26.83
7	Building brick	0.375	40	0.7	2.3	24.15
8	Paint	2.587	4	0.7	3.3	23.90
9	Bituminous materials	1.106	10	0.7	2.9	22.45
10	Stainless steel	1.000	15	0.6	2.1	18.90
11	Wood	10.875	30	0.03	1.8	17.61
12	Synthetic rubber	6.660	3	0.7	1.0	14.00
13	Carbon steel	13.000	18	0.02	2.3	10.76
14	Nickel	0.646	14	0.5	2.3	10.40
15	Building stone	0.095	50	0.7	2.3	7.65
16	Paper	20.927	3	0.06	2.0	7.53
17	Magnesium	0.590	12	0.4	2.3	6.5
18	Gold	0.124	39	0.6	2.0	5.80
19	Tin	0.506	13	0.4	2.1	5.53
20	Leather	5.146	5	0.2	1.0	5.15
21	Gray iron	3.216	20	0.03	2.0	3.86
22	Cotton (fiber)	3.336	6	0.1	1.9	3.80
23	Wool (fiber)	1.085	6	0.2	1.9	2.48
24	Urea and melamine (plastic)	0.420	27	0.2	1.0	2.27
25	Alloy steel	2.160	21	0.02	2.4	2.18
26	Lead	0.728	5	0.3	2.0	2.18
27	Phenolics (plastic)	0.366	27	0.2	1.0	1.98
28	Refractory ceramics	0.700	6	0.2	2.3	1.93
29	PVC (plastic)	0.700	11	0.2	1.0	1.54
30	Clay pipe	0.103	50	0.1	2.8	1.44
31	Polyesters (plastic)	0.228	30	0.2	1.0	1.37

TABLE IX (Concluded)

Rank	Material	Annual Production (billion $)	Economic Life (year)	Exposure Index*	Labor Content Factor	In-Place Material Exposed to Air Pollution (billion $)
32	Polyethylene (plastic)	0.975	6	0.2	1.0	1.17
33	Chromium	0.113	10	0.4	2.4	1.08
34	Acrylics (plastic)	0.278	12	0.3	1.0	1.00
35	Nylon (fiber)	0.830	6	0.1	1.9	0.95
36	Polystyrene (plastic)	0.850	5	0.2	1.0	0.85
37	Cellulose esters (fiber)	0.717	6	0.1	1.9	0.82
38	Polypropylene (plastic)	0.403	8	0.2	1.0	0.64
39	ABS (plastic)	0.278	11	0.2	1.0	0.61
40	Malleable iron	0.486	20	0.03	2.0	0.58
41	Silver	0.105	6	0.3	3.0	0.57
42	Natural rubber	1.790	6	0.05	1.0	0.54
43	Molybdenum	0.238	37	0.02	2.9	0.51
44	Epoxies (plastic)	0.147	16	0.2	1.0	0.47
45	Cellulosics (plastic)	0.228	7	0.2	1.0	0.40
46	Rayon (fiber)	0.288	6	0.1	1.9	0.33
47	Carbon and graphite	0.339	12	0.02	2.4	0.3
48	Acrylics (fiber)	0.170	6	0.1	1.9	0.19
49	Acetate (fiber)	0.165	6	0.1	1.9	0.19
50	Nylons (plastic)	0.106	8	0.2	1.0	0.17
51	Polyester (fiber)	0.136	6	0.1	1.9	0.16
52	Acetate (plastic)	0.058	10	0.2	1.0	0.12
53	Polyolefins (fiber)	0.036	6	0.1	1.9	0.04

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* The exposure index is the estimated fraction of material which is exposed directly to a polluted atmosphere.

CHAPTER VII

INTERACTIONS BETWEEN POLLUTANTS AND MATERIALS

ECONOMIC EFFECTS OF SOILING

Several approaches could be taken in an effort to measure economic loss due to soiling: (1) a consumer survey to determine the amount spent to remove the effects of soiling; (2) a survey of the cleaning industry to determine the volume of business attributable to air pollution; or (3) an investigation of changes in land values. Each of these methods would produce some value related to the amount that is actually spent or lost. The approach employed in this study was designed to assign an economic value to the loss in aesthetic beauty of an object caused by soiling. The method estimated the total area (weight) of material exposed and multiplied that quantity by the increased cost necessary to clean each unit area (weight) of this material to maintain it in a clean condition. The standard used for "clean" was considered the equivalent of a normal suburban residence.

Given a quantity (M) of a material, an analytical expression for the increased cost (L) of cleaning per year due to air pollution soiling may be written

$$L = M \gamma \Delta f$$

where γ is the cost of cleaning one unit of material, the unit being that of M ; Δf is the increased frequency of cleaning as a function of suspended particulate level. The value of γ for the purposes of this study was calculated for two classes of materials--fibers and nonfibers--based on the following assumptions: (a) the charge for cleaning fibers was figured on the basis of weight and was taken to be $.10 per pound, and (b) nonfibers were cleaned for $.10 per square foot. It may then be shown that

$$\gamma_{\text{fibers}} = \frac{0.10}{Rw}$$

$$\gamma_{\text{nonfibers}} = \frac{0.10}{Rw\rho t}$$

where the units of γ are dollars per dollar of goods; w is the material price per pound; R is the labor factor; ρ is the density; and t is the average thickness of the material.

The value of $.10 per square foot is based on the cost of cleaning windows and the labor cost of painting a building. Obviously this value does not hold true for all cleaning costs (washing a car, for example). The cleaning costs were really constructed with building structures in mind.

We then write the soiling damage cost as

$$L = M\nu \ ,$$

and identify M with the value of material exposed, given in Table IX and call ν the soiling interaction value which has units of yr^{-1}. It can be seen that

$$\nu_{fibers} = \frac{0.10\ \Delta f}{Rw}$$

$$\nu_{nonfibers} = \frac{0.10\ \Delta f}{Rw\rho t} \ .$$

Obtaining the value for Δf is the most difficult aspect of this problem. It must be obtained from surveys and necessarily involves judgments about such subjective areas as how clean people want their environment to be; how much they are willing to pay for the desired level of cleanliness; what they are willing to put up with; and other similar factors. The only data available were obtained by Michelson and Tourin in a series of studies (see AE-5, AE-6, AE-7, and AE-122) of cleaning frequencies of personal goods and residences as a function of suspended particulate level. This study was for various residential areas in upper Ohio, New England, and the Washington, D. C., area. The study showed that the frequency of cleaning is given approximately by

$$f = a + bF_p \ ,$$

and in the absence of pollution

$$f_o = a + bF_r$$

where F_p and F_r represent the concentration of suspended particulates measured in $\mu g/m^3$ for polluted and rural environments, respectively, and a and b are constants. Although a , and therefore f , varied from one location to another (perhaps reflecting cultural and economic heritage) b remained relatively constant for a particular cleaning operation. Obviously, the increased frequency Δf due to suspended particulates is

$$\Delta f = f - f_o$$

$$\Delta f = b(F_p - F_r) .$$

The cleaning frequency given by Michelson was adjusted by a factor s so that

$$\Delta f = sb(F_p - F_r) ,$$

where s is included in the cleaning frequency in an effort to account for the fact that some materials (such as clay pipe, refractory ceramics, and gray iron) are seldom, if ever, cleaned. This factor is somewhat subjective but the following guidelines were followed:

1. Those materials used in heavy machinery or heavy industrial applications were given a value of 0.0, meaning that soiling of these materials is of no concern.

2. All building materials, fibers (fabrics), and decorative materials were assigned a value of 1.0; that is, all those materials which lose aesthetic value when soiled.

3. Other materials, such as paper, leather, and plastics, were assigned intermediate values to account for that proportion that is normally cleaned or desired to be clean.

Michelson and Tourin's (AE-5) data are presented as straight line functions relating frequency of cleaning to suspended particulate levels. The slopes of these lines range from 0.006 for outside walls of a frame house to 0.017 for outside windows in winter. Therefore, somewhat arbitrarily, the values 0.01 are used for fibers, glass, and leather and 0.006 for all other materials. These values are then multiplied by the difference in average suspended particulate levels at urban and rural areas to obtain the frequency difference Δf . The levels, 100 and 40 $\mu g/m^3$, respectively, were used in this study.

It must be noted that the increased frequency of cleaning obtained in this manner is strictly true only for those areas in which the studies were made. Also, the actual dollar costs are applicable only to those materials for which people are willing to make the effort to keep them as clean as their own homes. Thus, the dollar value resulting from application of this value does not reflect what is actually spent, but what would be spent *if* the entire urban-industrial environment were to be kept as clean as people keep their own homes.

ECONOMIC EFFECTS OF CHEMICAL POLLUTANTS

The chemical deterioration interaction value (ν) is defined as the average fractional loss of useful life per year for any material exposed in a polluted environment above the deterioration suffered in an unpolluted (rural) environment. It was originally planned to obtain a damage function for each material-pollutant combination. It was hoped that all of these could be basic values based upon test samples so that they would be independent of the final form and use of the material; in this manner, maximum objectivity would be maintained. If interaction rates r had been available, say in the form $r = \varphi$ per year per F_i where φ is an appropriate physical unit, say thickness, weight, or percent tensile strength, and F_i is the concentration of the i^{th} pollutant, then by knowing the use of the material or its average size (φ_{avg}) and the pollutant concentration, the loss of value per year per pollutant could be calculated simply as

$$L = \frac{Mr\ F_i}{\varphi_{avg}}$$

$$= M\nu$$

$$\nu = \frac{rF_i}{\varphi_{avg}}$$

For example, if r were the corrosion rate expressed as inches per year, then φ_{avg} would be the average thickness of the material.

Unfortunately, such values were available for only a few materials. Where data were not available, a reasonable estimate was made to provide a basis on which to make tentative calculations. The procedure for obtaining the chemical deterioration interaction values is discussed by classes of materials in the following section.*

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* See Appendix E for expanded discussions of interaction values for selected materials.

Metals

Over the past 50 years, much effort has gone into exposure testing of metals, both ferrous and nonferrous. Many people and laboratories have been engaged in these efforts, but by far the greatest amount of work has been directed or collected by the ASTM. The primary efforts of the ASTM in the field of atmospheric corrosion of metals have been to determine, by actual exposure, the weight loss and corrosion depth of various metals exposed at various sites.

The samples are generally metal panels with about 50 square inches surface area; these are exposed at typical rural, industrial, urban, and marine test sites. Rural is usually State College, Pennsylvania; industrial is Newark, New Jersey; New York, New York; or Pittsburgh, Pennsylvania; marine is Kure Beach, North Carolina. Concentrations of pollutants were not usually measured; also, the exposure tests covered 10- to 20-year periods. It is, therefore, safe to assume that the pollution levels changed considerably during the course of the tests, at least in "industrial" locations. Because of these limitations, there is little hope of accurately attributing the damage to a specific pollutant.

Corrosion rates are typically reported in mils per year (loss of thickness in 0.001 inch per year) or mdd (weight loss expressed in milligrams per square decimeter per day). These two units are usually interchanged, so that a value which was actually obtained by measuring the loss of weight may be reported as a loss of thickness. Pitting corrosion is reported in mils per year and cannot be converted to weight loss rates.

Subject to the conditions mentioned above, corrosion rates were obtained from the literature. When a number of independent measurements existed, the average of the reported values was used, and a value of interaction was calculated.

The first step in the procedure was to obtain the difference between the average industrial and the average rural corrosion rates r_i and r_r, respectively, expressed in inches per year; the difference between the two was attributed to pollution (in most cases there was at least an order of magnitude difference between the two rates). The next step was to calculate the value of interaction $\nu = (r_i - r_r)/t$ where t is the average thickness. The average thickness was estimated based on knowledge of the distribution of uses for a metal. In the case of zinc, for example, 50 percent goes into protective coatings, 0.001 inch thick; most of the rest goes into alloys and castings with an average thickness of 0.2 inch thick. When zinc is weighted by the economic lifetime, one obtains an average thickness of 0.003 inch. Of course, it must be acknowledged that zinc coatings range from less than 0.0001 inch to more than 0.0025 inch, but the average value obtained is quite reasonable.

These calculations were made for each metal except gold. The value for gold was simply estimated at a 10,000-year lifetime. The results along with the average thickness and corrosion rates, are shown in Table X.

TABLE X

CORROSION RATES FOR SELECTED METALS

Material	Corrosion Rate (mils/yr)	Average Thickness (in.)	Value of Interaction (yr^{-1})
Ferrous Metals			
Gray iron	0.5	1.0	0.50×10^{-3}
Malleable iron	0.5	0.3	0.16×10^{-2}
Alloy steel	0.59	0.15	0.40×10^{-2}
Carbon steel	0.39	0.078	0.50×10^{-2}
Stainless steel	0.003	0.035	0.85×10^{-4}
Nonferrous Metals			
Aluminum	0.048	0.023	0.21×10^{-2}
Brass and bronze	0.042	0.1	0.42×10^{-3}
Chromium	0.002	0.0027	0.75×10^{-3}
Copper	0.025	0.0125	0.20×10^{-2}
Gold	0.00022	0.0022	0.10×10^{-3}
Magnesium	0.65	0.25	0.26×10^{-2}
Molybdenum	0.026	0.1	0.26×10^{-3}
Lead	0.0025	0.022	0.11×10^{-3}
Nickel	0.058	0.0023	0.25×10^{-1}
Silver	0.025	0.02	0.12×10^{-2}
Tin	0.8	0.031	0.26×10^{-1}
Zinc	0.09	0.0031	0.29×10^{-1}

Stone, Clay, and Glass

In this category, only the effects of SO_2 on building stone have been discussed to any extent. It is agreed that SO_2 does attack stone, but the literature usually speaks only of isolated incidents where some catastrophic failure has resulted. Stone, clay, and glass have not been subject to careful exposure tests as is the case with metals. Also, no attempts have been made to assign deterioration rates as a result of pollution. The literature contains only one passing comment to the effect that one-half the exposed building stone suffers an increased deterioration rate of 0.5 percent per year. This value was used in this study for building stone, and provided the basis for the estimated values for building brick, clay pipe, and concrete. The value used--0.001 per year--seems conservative in view of the damage reported in the literature.

No values were available for deterioration of ceramics, glass, carbon, and graphite. There was an occasional mention of an incident of hydrofluoric acid in sufficient quantities in the atmosphere to etch glass. An interaction value was therefore chosen; the value was small enough to recognize that there is no significant damage, but large enough to allow for the possibility of an isolated incident.

Plastics and Rubber

Very little data on plastics or rubber are available which may be used in the context of this study. Certainly much work has been done investigating the reaction of ozone with rubber. However, reaction rates reported in the literature indicate, for an urban-industrial ozone level, crack propagation rates from 10^{-4} inch per year to 10^{3} inch per year. The problem,of course, is that natural rubber and many synthetic rubbers fail catastrophically in a very short period of time in the presence of even low levels of ozone. As the result of an intensive research effort from 1940 to 1960, the problem was understood, and additives were developed to prevent or retard crack growth. Consequently, most rubber products are designed to survive their economic life in a given location. There are no surveys of studies upon which to base actual loss of useful life. For this project an interaction value of 0.1 per year was chosen. This value is small enough to allow the average rubber product to perform for the three-year estimated economic life and yet is large enough to amount to significant losses (mostly by premature failure before the end of its useful life).

The choice of an interaction value for plastics is even more difficult. The field of plastics is surrounded by some mystic aura--one moment plastics are said to be indestructible and impervious to chemical attack, and the next moment it is admitted that a small concentration of some pollutant, usually oxidant or organic, leads to catastrophic failure. There have been no studies to correlate plastics failure with air pollutants. The only exposure studies are for hot and dry, hot and humid, and moderate climates. If deterioration rates are used from these studies, and only one-half the damage is attributed to air pollutants, the result gives deterioration rates much higher than the estimated economic lifetimes will allow. Consequently, a conservative estimate of 0.01 was chosen and uniformly applied to all plastics; thus the ranking of plastics among themselves is strictly on the basis of the amount (dollar value) in use.

Fibers

The value of interaction for fibers suffers from the same problem as that for plastics: lack of research. Only for cotton have exposure tests been conducted that produced useful results. Correlation of damage due to SO_2 and O_3 has been found, while damage by NO_x is suspected. A reasonable use of these data gives a value of interaction of 0.04. For lack of any better information, the same value was applied to all other fibers.

Finishes and Coatings

Finishes and coatings, of which the primary concern is with the subclass paint, are subjected more severely to the ravages of air pollution than any other material, and possibly suffer the greatest actual economic loss. As a result, they have been the subject of intensive study. However, all known efforts to correlate the actual loss of useful life with pollutants have been unsuccessful. The figure used most often when discussing this problem is that one must paint every four years in a polluted environment instead of every five years in an unpolluted environment (see Appendix E). Taking this statement at face value, a reasonable value of interaction of 0.05 is obtained.

Other Materials

Wood, paper, leather, and bituminous materials are similar to the other nonmetals in that very little is known about their resistance to air pollution. The attack of SO_2 on paper and leather has been observed and reported, but in most cases no reaction rates have been assigned. No mention of damage to wood by pollution was seen in the literature although behavior similar to that of cotton might be expected. Bituminous materials are generally used as protective materials, and as a consequence must suffer only slight economic damage compared to the materials they are to protect. Thus, guided by several suggestions in the literature and on intuitive feelings, the following values of interaction were chosen: wood, 0.001; paper 0.003; leather, 0.004; and bituminous materials, 0.0001.

RESULTS

Interaction values for soiling and deterioration have been collected and are presented in Table XI.

TABLE XI

VALUES OF INTERACTION

Material	Value of Interaction (yr^{-1})	
	Soiling	Deterioration
Ferrous Metals		
Gray iron	0.0	0.50×10^{-3}
Malleable iron	0.0	0.16×10^{-2}
Alloy steel	0.0	0.40×10^{-2}
Carbon steel	0.0	0.50×10^{-2}
Stainless steel	0.72×10^{-2}	0.85×10^{-4}
Nonferrous Metals		
Aluminum	0.90×10^{-1}	0.21×10^{-2}
Brass and bronze	0.50×10^{-2}	0.42×10^{-3}
Chromium	0.15×10^{0}	0.75×10^{-3}
Copper	0.35×10^{-2}	0.20×10^{-2}
Gold	0.13×10^{-3}	0.10×10^{-3}
Magnesium	0.26×10^{-3}	0.26×10^{-2}
Molybdenum	0.0	0.26×10^{-3}
Lead	0.30×10^{-1}	0.11×10^{-3}
Nickel	0.96×10^{-1}	0.25×10^{-1}
Silver	0.72×10^{-3}	0.12×10^{-2}
Tin	0.96×10^{-2}	0.26×10^{-1}
Zinc	0.90×10^{0}	0.29×10^{-1}
Stone, Clay, and Glass		
Building stone	0.90×10^{-2}	0.23×10^{-2}
Building brick	0.47×10^{-2}	0.10×10^{-2}
Clay pipe	0.0	0.10×10^{-2}
Cement and concrete	0.17×10^{-1}	0.10×10^{-2}
Refractory ceramics	0.0	0.10×10^{-4}
Flat glass	0.66×10^{0}	0.10×10^{-4}
Carbon and graphite	0.0	0.10×10^{-5}
Plastics and Rubber		
Synthetic rubber	0.50×10^{-2}	0.10×10^{0}
Natural rubber	0.0	0.10×10^{0}
Polyethylene	0.50×10^{0}	0.10×10^{-1}
PVC	0.10×10^{1}	0.10×10^{-1}

TABLE XI (Concluded)

	Value of Interaction (yr^{-1})	
Material	Soiling	Deterioration
Plastics and Rubber (Concluded)		
Polystyrene	0.26×10^{1}	0.10×10^{-1}
Phenolics	0.20×10^{1}	0.10×10^{-1}
Polypropylene	0.14×10^{0}	0.10×10^{-1}
Urea and melamine	0.27×10^{-1}	0.10×10^{-1}
Polyesters	0.30×10^{-1}	0.10×10^{-1}
ABS	0.14×10^{0}	0.10×10^{-1}
Acrylics	0.57×10^{-1}	0.10×10^{-1}
Cellulosics	0.25×10^{-1}	0.10×10^{-1}
Epoxies	0.24×10^{-1}	0.10×10^{-1}
Acetate	0.10×10^{-1}	0.10×10^{-1}
Nylons	0.17×10^{0}	0.10×10^{-1}
Fibers		
Cotton	0.90×10^{-1}	0.40×10^{-1}
Wool	0.22×10^{-1}	0.40×10^{-1}
Rayon	0.10×10^{0}	0.40×10^{-1}
Acetate	0.78×10^{-1}	0.40×10^{-1}
Acrylics	0.26×10^{-1}	0.40×10^{-1}
Polyester	0.21×10^{-1}	0.40×10^{-1}
Nylon	0.15×10^{-1}	0.40×10^{-1}
Polyolefins	0.35×10^{-1}	0.40×10^{-1}
Cellulose esters	0.54×10^{-1}	0.40×10^{-1}
Finishes and Coatings		
Paint	0.15×10^{1}	0.50×10^{-1}
Other Materials		
Wood	0.14×10^{-3}	0.10×10^{-2}
Paper	0.15×10^{0}	0.30×10^{-2}
Leather	0.48×10^{0}	0.40×10^{-2}
Bituminous materials	0.12×10^{-2}	0.10×10^{-3}

CHAPTER VIII

SIGNIFICANCE OF POLLUTANT-MATERIAL COMBINATIONS

ECONOMIC RANKING

The total value of materials exposed to air pollution (from Chapter VI) and the values of interaction between the various materials and pollutants (from Chapter VII) have been combined to produce a single figure representing the extent of economic damage attributable to particulate pollutants (soiling effects) and gaseous pollutants (chemical effects). These damage factors are summarized and ranked in Tables XII and XIII.

The value of economic damage was calculated as a series of products. These products include the following variables:

1. Annual production value of the material.

2. Expected economic life of the material.

3. Portion of the material, by the nature of its use, actually exposed to air pollutants.

4. Labor content factor.

5. Susceptibility of the material to pollutants, measured in terms of a value of interaction.

The damage factors thus obtained give a good indication of the relative economic importance of materials affected by air pollution.*

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* Another approach has been taken in which the potential damage loss has been calculated, i.e., the damage which would be possible if no effort was made to protect materials. This method would indicate approximately how much effort has gone towards protecting various materials. This approach is presented in Appendix F.

TABLE XII

SOILING

Rank	Material	Soiling Interaction Factor (yr^{-1})	In-place Unprotected Materials Value (Billion $)	Soiling Cost (Billion $)
1	Paint	$0.15 \times 10^{+1}$	23.9	35.0
2	Zinc	0.90×10^{0}	26.8	24.0
3	Flat glass	0.66×10^{0}	28.6	19.0
4	Cement and concrete	0.17×10^{-1}	316.2	5.4
5	Aluminum	0.90×10^{-1}	54.1	4.9
6	Leather	0.48×10^{0}	5.15	2.5
7	Polystyrene (plastic)	$0.26 \times 10^{+1}$	0.85	2.2
8	PVC (plastic)	$0.10 \times 10^{+1}$	1.54	1.54
9	Paper	0.15×10^{0}	7.53	1.12
10	Nickel	0.96×10^{-1}	10.40	1.00
11	Polyethylene (plastic)	0.50×10^{0}	1.17	0.59
12	Cotton (fiber)	0.90×10^{-1}	3.80	0.34
13	Copper	0.35×10^{-2}	54.90	0.19
14	Brass and Bronze	0.50×10^{-2}	33.12	0.17
15	Chromium	0.15×10^{0}	1.08	0.16
16	Stainless steel	0.72×10^{-2}	18.90	0.14
17	Building brick	0.47×10^{-2}	24.15	0.11
18	Polypropylene (plastic)	0.14×10^{0}	0.64	0.090
19	ABS (plastic)	0.14×10^{0}	0.61	0.085
20	Synthetic rubber	0.50×10^{-2}	14.00	0.070
21	Building stone	0.90×10^{-2}	7.65	0.069
22	Lead	0.30×10^{-1}	2.18	0.065
23	Urea and Melamine (plastic)	0.27×10^{-1}	2.27	0.061
24	Wool	0.22×10^{-1}	2.48	0.055
25	Tin	0.96×10^{-2}	5.53	0.053
26	Cellulose ester (fiber)	0.54×10^{-1}	0.82	0.044
27	Polyesters (plastic)	0.30×10^{-1}	1.37	0.041
28	Phenolics	0.20×10^{-1}	1.98	0.040
29	Rayon (fiber)	0.10×10^{0}	0.33	0.033
30	Nylon (plastic)	0.17×10^{0}	0.17	0.029
31	Bituminous materials	0.12×10^{-2}	22.45	0.027
32	Acrylics (plastic)	0.26×10^{-1}	1.00	0.026
33	Wood	0.14×10^{-3}	17.61	0.025
34	Acetate (fiber)	0.78×10^{-1}	0.19	0.015
35	Nylon (fiber)	0.15×10^{-1}	0.95	0.014
36	Epoxies (plastic)	0.24×10^{-1}	0.47	0.011
37	Cellulosics (plastic)	0.25×10^{-1}	0.40	0.010
38	Acrylics (fiber)	0.26×10^{-1}	0.19	0.005
39	Polyesters (fiber)	0.21×10^{-1}	0.16	0.003
40	Magnesium	0.26×10^{-3}	6.50	0.002
41	Acetate (plastic)	0.10×10^{-1}	0.12	0.001
42	Polyolefin (fiber)	0.35×10^{-1}	0.04	0.001
43	Gold	0.13×10^{-3}	5.80	< 0.001
44	Silver	0.72×10^{-3}	0.57	< 0.001
45	Gray iron	No effect		
46	Malleable iron	No effect		
47	Alloy steel	No effect		
48	Molybdenum	No effect		
49	Clay pipe	No effect		
50	Refractory ceramics	No effect		
51	Carbon and graphite	No effect		
52	Natural rubber	No effect		
53	Carbon steel	No effect		
			TOTAL	100.0

TABLE XIII

DETERIORATION

Rank	Material	Value of (yr^{-1}) Interaction	In-Place Value of Materials Exposed (Billion $)	Value Economic Loss (Million $)
1	Paint	0.50×10^{-1}	23.9	1,195.0
2	Zinc	0.29×10^{-1}	26.83	778.0
3	Cement and concrete materials	0.10×10^{-2}	316.21	316.0
4	Nickel	0.25×10^{-1}	10.40	260.0
5	Cotton (fiber)	0.40×10^{-1}	3.80	152.0
6	Tin	0.26×10^{-1}	5.53	144.0
7	Synthetic rubber	0.10×10^{0}	14.00	140.0
8	Aluminum	0.21×10^{-2}	54.08	114.0
9	Copper	0.20×10^{-2}	54.88	110.0
10	Wool (fiber)	0.40×10^{-1}	2.48	99.2
11	Natural rubber	0.10×10^{0}	0.54	54.0
12	Carbon steel	0.50×10^{-2}	10.76	53.8
13	Nylon (fiber)	0.40×10^{-1}	0.95	38.0
14	Cellulose ester (fiber)	0.40×10^{-1}	0.82	32.8
15	Building brick	0.10×10^{-2}	24.15	24.2
16	Urea and melamine (plastic)	0.10×10^{-1}	2.27	22.7
17	Paper	0.30×10^{-2}	7.53	22.6
18	Leather	0.40×10^{-2}	5.15	20.6
19	Phenolics (plastic)	0.10×10^{-1}	1.98	19.8
20	Wood	0.10×10^{-2}	17.61	17.6
21	Building stone	0.23×10^{-2}	7.65	17.6
22	PVC (plastic)	0.10×10^{-1}	1.54	15.4
23	Brass and bronze	0.42×10^{-3}	33.12	13.9
24	Polyesters (plastic)	0.10×10^{-1}	1.37	13.7
25	Rayon (fiber)	0.40×10^{-1}	0.33	13.2
26	Magnesium	0.20×10^{-2}	6.50	13.0
27	Polyethylene (plastic)	0.10×10^{-1}	1.17	11.7
28	Acrylics (plastic)	0.10×10^{-1}	1.00	10.0
29	Alloy steel	0.40×10^{-2}	2.18	8.7
30	Polystyrene (plastic)	0.10×10^{-1}	0.85	8.5
31	Acrylics (fiber)	0.40×10^{-1}	0.19	7.6
32	Acetate (fiber)	0.40×10^{-1}	0.19	7.6
33	Polyesters (fiber)	0.40×10^{-1}	0.16	6.4
34	Polypropylene (plastic)	0.10×10^{-1}	0.64	6.4
35	ABS (plastic)	0.10×10^{-1}	0.61	6.1
36	Epoxies (plastic)	0.10×10^{-1}	0.47	4.7
37	Cellulosics (plastic)	0.10×10^{-1}	0.40	4.0
38	Bituminous materials	0.10×10^{-3}	22.45	2.2
39	Gray iron	0.50×10^{-3}	3.86	1.9
40	Nylon (plastic)	0.10×10^{-1}	0.17	1.7
41	Polyolefins (fiber)	0.40×10^{-1}	0.04	1.6
42	Stainless steel	0.85×10^{-4}	18.90	1.6
43	Clay pipe	0.10×10^{-2}	1.44	1.4
44	Acetate (plastic)	0.10×10^{-1}	0.12	1.2
45	Malleable iron	0.16×10^{-2}	0.58	0.9
46	Chromium	0.75×10^{-3}	1.08	0.8
47	Silver	0.12×10^{-2}	0.57	0.7
48	Gold	0.10×10^{-3}	5.80	0.6
49	Flat glass	0.10×10^{-4}	28.59	0.3
50	Lead	0.11×10^{-3}	2.18	0.2
51	Molybdenum	0.25×10^{-3}	0.51	0.1
52	Refractory ceramics	0.10×10^{-4}	1.93	0.02
53	Carbon and graphite	0.10×10^{-5}	0.30	0.00
			TOTAL	3,800

SENSITIVITY OF FINAL RANKING TO DATA ERRORS AND ASSUMPTIONS

Every method of study is subject to limitations. Two limitations of a quantitative analysis are: (1) they can be no more accurate than the data used to make them and (2) they necessarily must make assumptions about the state of the real world that may be only partially true. The final ranking of materials by value of economic loss is subject to these limitations. In order to give some insight into how sensitive the ranking is to data errors and assumptions, a sensitivity analysis was prepared.

The estimates for each of the variables involved--annual production rate, the expected life of the material, percentage of material exposed to air pollution, and a value of interaction--are subject to considerable uncertainty. (The uncertainty in these estimates increases in the order in which the variables are named.) When two or more independent variables are multiplied together, any inaccuracies in the individual variables will be amplified in their product. This study assumes that the resulting product, the value of economic loss, falls within a range of a factor of 10. Thus, the actual value of an indicated figure might be from roughly a third of the indicated amount to three times the amount given. For example, the expected value of economic loss for cotton material is calculated as $152 million. Therefore, the final assumption is that the real value of economic loss for cotton falls within an order of magnitude (within a range) from $48 million to $480 million.

The sensitivity of the final ranking to data errors and assumptions is determined by using a multiple range statistical test. The test is designed to separate a rank order listing into a set of classes. The members of one of these given classes cannot be statistically distinguished from one another. However, the members of a given class are statistically different (at a 95 percent confidence level) from the excluded members. This test is used to distinguish between three types of classes:

1. Materials that have no statistical difference in the value of economic loss.

2. Materials that have significantly more economic loss.

3. Materials that have significantly less economic loss.

The criteria for distinguishing two ranks (i and j) is the observed ratio $X_i/X_j > 10^{LSR/6}$ where LSR is a tabulated value (of the studentized range distribution) which varies slightly depending upon the separation of i and j . To determine the class sets for the ranks, we listed the expected values of economic loss X_i in rank order, X_1 being largest, X_{53} the smallest. Ranks i and j are chosen so that the ratio $X_i/X_j > 10^{3.48/6}$ separates the i^{th} and j^{th} material into statistically distinguishable classes. The results of this procedure for all ranks are shown in Figures 2 and 3.

Figure 2 is a graphical presentation of the statistical analysis to determine the sensitivity of the final ranked order list by economic loss due to deterioration. Figure 3 shows comparable data for the rankings of economic losses due to soiling. The vertical axes on the graphs indicate the economic ranking of pollutant-material damage. The horizontal scales indicate the probable range of the high and low rank for each material. For example, in Figure 2 nickel is ranked fourth, but because of the uncertainty of data, nickel may be ranked as low as ninth or as high as second. This means the economic damage to nickel, with 95 percent confidence, is more than that to wool, natural rubber, and carbon steel, which are ranked 10, 11 and 12, respectively.

A conservative estimate of the possible error in the calculation of economic loss does not cause a major shift in the relative ranking of an individual material. In other words, with 95 percent confidence, those materials ranked high should always be ranked high even though a degree of uncertainty may exist as to the absolute value of material-pollution damage; conversely, those materials ranked low should always be ranked low. Therefore, the relative importance of such material-pollution damage can be closely assessed.

MATERIALS AND PARTICULATE POLLUTANTS

The soiling matrix was constructed in a manner that gave weight to those materials with the largest surface area; no distinction was made for any possible difference in soiling or cleaning mechanisms between materials (see Table XII). The results, therefore, are not surprising. The top 10 ranked materials account for 97 percent of the damage. It is encouraging to note that the top three materials are protective coatings. By design, these materials are exposed directly, and would naturally be expected to rank first.

The two materials that seem out of place in the rankings are building brick, ranked 17th, and building stone, ranked 21st. This is much lower than was anticipated. At first, this ranking appears to be questionable because, when one visits a heavily polluted city, one is struck by the soiled state of stone and brick buildings. However, this results from several causes. First, these buildings have been accumulating dirt for 10 to 50 years, or even longer, and this amplifies the effect. Second, the buildings that one notices are usually churches, monuments, museums, government

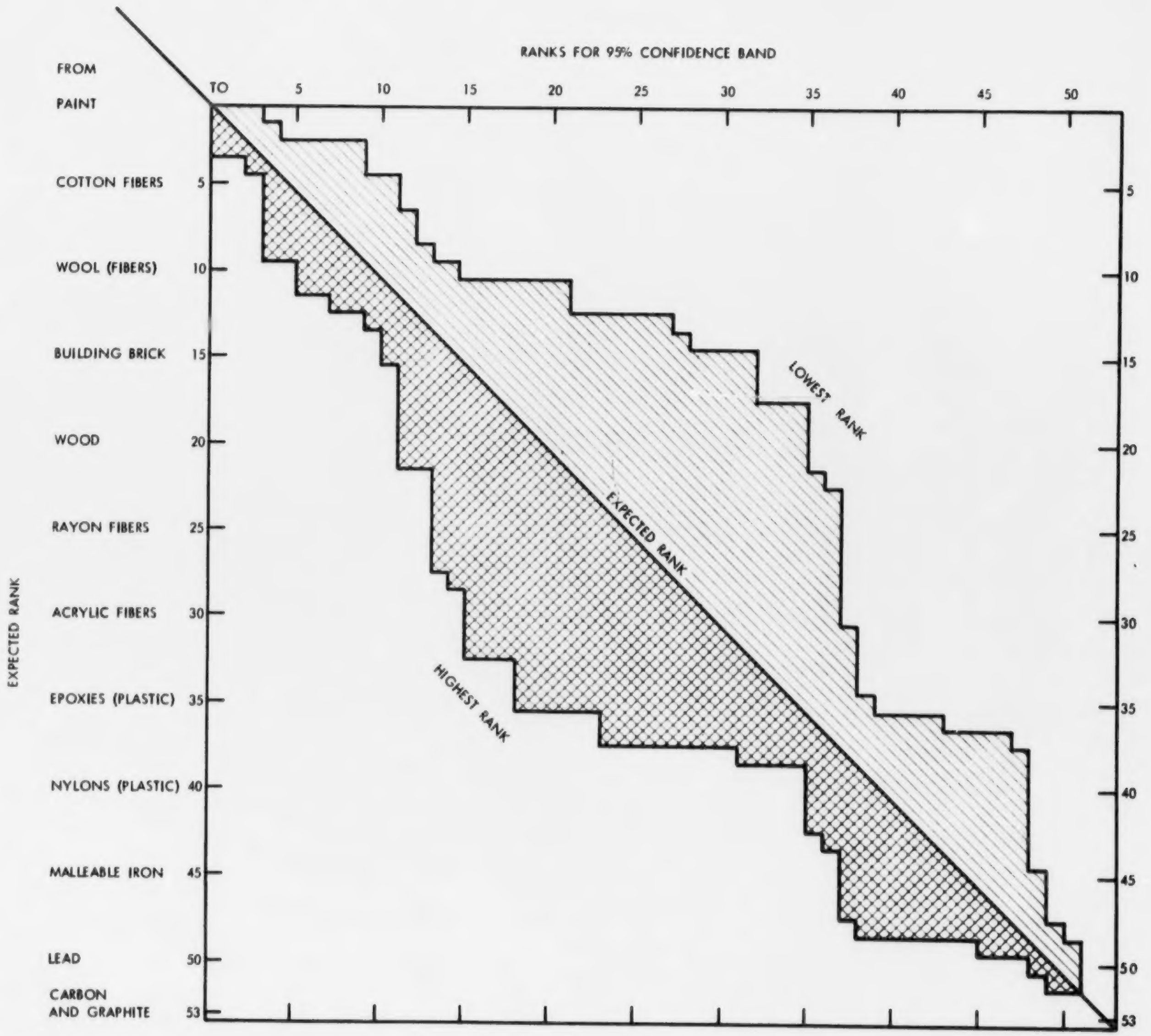

Figure 2 - Sensitivity Analysis of Final Ranking of Economic Loss Due to Deterioration

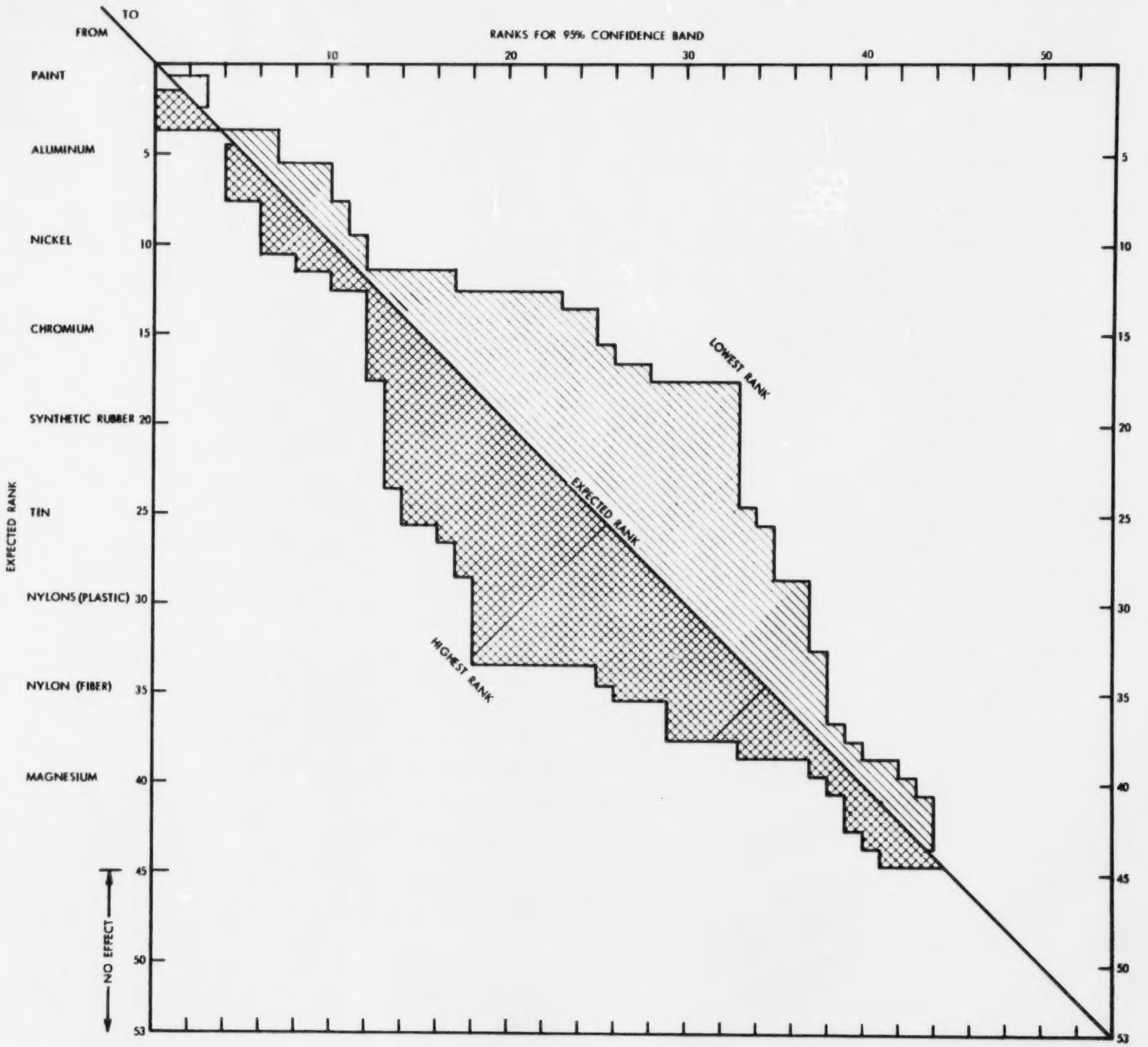

Figure 3 - Sensitivity Analysis of Final Ranking of Economic Loss Due to Soiling

buildings, and other structures which further magnify the appearance of the amount of damage.

The sum of soiling costs in Table XII is approximately \$100 billion. If we assume a factor of 10 error range, the true value should be between \$31 and \$310 billion.

Two studies by Michelson and Tourin (AE-6, AE-7) between 1966 and 1968 found that an average suspended particulate level of 100 $\mu g/m^3$ caused an increase in the per capita cost of maintenance of household items of approximately \$200 per year. Assuming that 75 percent of the U. S. population is subjected to such pollution levels, this gives an annual cost of \$30 billion. In comparing Michelson and Tourin's estimate with ours it must be remembered that their estimate was for actual expense incurred and only for household items. Since our estimate includes all commercial, industrial, and public buildings and materials and is an estimate of what it would cost _if_ all were kept clean, it appears to be a reasonable estimate.

The size of this estimate means that the only way that the buildings and materials in our urban areas will be kept clean is by considerably reducing the average suspended particulate levels.

MATERIALS AND CHEMICAL POLLUTANTS

The result of combining the interaction value for chemical deterioration with the economic value of materials is the rank ordering of economic loss factors shown in Table XIII. To interpret these results, it is imperative that one realize that the individual material loss estimates were made to determine relative importance rather than actual value. However, the \$3.8 billion, which is the sum of the economic losses, appears to be a reasonable estimate. If we assume that this list of materials represents only 40 percent of the total value of materials exposed to air pollution and that damage functions for the remaining 60 percent are similar, the total loss due to chemical attack on materials by air pollution is estimated at \$9.5 billion.

In calculating the losses to individual materials the same damage function was used for all plastics, another, for all fibers, and another for both natural and synthetic rubber. If we lump these generic classes, the number of materials is reduced to 32 and it becomes easier to visualize the relative importance of each type of damage.

These results are reranked in Table XIV along with percentages of total damage for each material and the accumulative percentage according to rank. The first two materials account for approximately 51 percent of the

TABLE XIV

RANKING OF ECONOMIC LOSSES CAUSED BY DETERIORATION

Rank	Material	Economic Loss (Million $)	Percent of Total	Accumulative Percent of Total
1	Paint	1,195.0	31.5	31.5
2	Zinc	778.0	20.4	51.9
3	Fibers	358.0	9.4	61.3
4	Cement and concrete	316.0	8.3	69.6
5	Nickel	260.0	6.8	76.4
6	Rubber	194.0	5.0	81.4
7	Tin	144.0	3.8	85.2
8	Plastics	126.0	3.3	88.5
9	Aluminum	114.0	3.0	91.5
10	Copper	110.0	2.9	94.4
11	Carbon steel	53.8	1.4	95.8
12	Building brick	24.2	0.6	96.4
13	Paper	22.6	0.6	97.0
14	Leather	20.6	0.55	97.5
15	Wood	17.6	0.46	98.0
16	Building stone	17.6	0.46	98.5
17	Brass and Bronze	13.4	0.35	99.0
18	Magnesium	13.0	0.35	99.4
19	Alloy steel	8.7	0.23	99.6
20	Bituminous materials	2.2	0.06	99.7
21	Gray iron	1.9	0.05	99.8
22	Stainless steel	1.6	0.04	99.8
23	Clay pipe	1.4	0.03	99.9
24	Malleable iron	0.9	Insignificant	
25	Chromium	0.8	Insignificant	
26	Silver	0.7	Insignificant	
27	Gold	0.6	Insignificant	
28	Glass	0.3	Insignificant	
29	Lead	0.2	Insignificant	
30	Molybdenum	0.1	Insignificant	
31	Refractory ceramincs	0.02	Insignificant	
32	Carbon and graphite	0.003	Insignificant	
	TOTAL	3,800.0		

total loss while the last 20 account for only a little over 3 percent of the total loss.

Conclusions

Our calculations show that the loss caused by the action of air pollution on materials is primarily due to particulates. However, attack by gaseous pollutants on paints, metals, plastics, fibers, and rubber appear to cause sufficient damage to warrant the use of relatively expensive control measures. One must also remember that we have not included second order effects such as lost machine time during maintenance operations nor cost of replacement, both being beyond the scope of this program.

CHAPTER IX

IDENTIFICATION OF INFORMATION GAPS

Technological Gaps and Research Needs

Economic analysis and sociological study can indicate the amount of potential economic damage and public reaction to pollution effects on materials. Both of these areas, however, are affected so greatly by feedback or secondary effects that precise evaluation is impossible. Economic effects, even if the physical and chemical details of corrosion were known, would be obscured by the fact that material selection has often reduced the problem at the cost of more expensive material. How then does one decide whether the low loss rate for a particularly durable material implies a low economic effect or the high cost of the durable material implies a high economic effect? In addition, the public has adapted itself to many of the effects and, to a large extent, accepts soiling, repair, refinishing, and other consequences as a normal part of modern life.

Of particular interest is the dearth of information concerning the dosage-response relations for commercial materials in pollutant concentrations that are typical of actual atmospheres. It is also interesting to notice the distribution of literature among the leading 53 materials. Almost 50 percent of the material reviewed has no bearing on any specific material-pollutant problem. Even the remaining half gives virtually no dosage-response information from which damage rates could be computed or even closely estimated. Much which as been presented as "technical literature" is in fact little more than editorial commentary.

Literature Commentary

Each article, report and book which was acquired was read and classified according to its contents. Specifically, they were grouped according to the material-pollutant combination(s) each dealt with. These results are shown in Appendix A. We shall now discuss the state of the art and technological gaps of the field of effects of air pollution on materials in terms of the distribution of literature.

At once we see that three categories of materials have received considerable attention: metals, rubber, and finishes and coatings. Cotton, almost in a category by itself, has also been studied quite extensively. A quick generalization, based again solely on the quantity of publications, (see Appendix A) identifies SO_x as the major cause of damage to metals; O_3 as the almost sole cause of damage to rubber; and both SO_x and O_3

as the cause of damage to cotton, and finishes and coatings. The interaction of metals with other inorganic pollutants has also been investigated considerably (other inorganic pollutants refer primarily to HCl, H_2S, and NH_3, approximately in that order of importance). Most of the articles listed under the general class of finishes and coatings and under NO_x and O_3 are concerned with the behavior of dyes. Most of the articles listed under the general class of stone, clay, and glass deal with the soiling of buildings.

Metals

The three best books available concerning damage to metals by air pollution are Metal Corrosion in the Atmosphere (ASTM Spec. Tech. Pub. 435, 1968); U. R. Evans, Corrosion and Oxidation of Metals - Scientific Principles and Practical Applications (Arnold, London, 1960); and, H. H. Uhlig, Ed., The Corrosion Handbook (John Wiley and Sons, N. Y., 1948). The work by Evans is a collection of facts gleaned from work done prior to 1960. Uhlig's book has a thorough search of all exposure tests prior to 1948. The latest book, which is the proceedings of an ASTM Symposium, contains valuable up-to-date information on exposure tests.

The majority of the exposure studies in the United States have been done under the direction of the ASTM. A great deal of early work was done in England, principally because of the highly corrosive nature of the atmosphere of heavily industrialized England. A reasonable amount of work has been reported in the German and Japanese languages, but was not reviewed for this study.

The metals extensively covered in the literature are alloy and carbon steels, aluminum, copper, nickel, and zinc. The reason is obviously the extensive use of these materials in construction. In general, the work which is reported in the literature is based upon samples exposed at a variety of locations with the weight loss per year measured. Identification of the cause of corrosion has usually been qualitative. The best correlation studies to date (Guttman and Sereda (BE-7)) have only been able to correlate the corrosion rate of zinc with the SO_2 level and time of wetness (of the zinc). Attempts to correlate corrosion rates of other metals with specific pollutants have been unsuccessful.

Stone, Clay, and Glass

In this class, the deterioration of building stone by SO_x and CO_2 has been recorded in the literature. Reports of damage to stone are sporadic, and in general deal only with monuments that mean a lot to people, and that have suddenly shown severe signs of deterioration, such as is happening in Venice, Italy (AE-124). Even though the attack of stone products may be comparable to or even greater than that of metals when expressed in inches per year, it is not as easily noticed because stone products are typically used in forms 10 to 10,000 times as thick as metals. As a result, such attack has not attracted much attention, and no effort comparable to the research on metals has been undertaken. Even so, the few published results show that the damage to stone structures by a polluted atmosphere is very real.

Plastics and Rubber

In this class, almost all the research effort expended has been directed toward the problem of ozone cracking of rubber. The attack on rubber by ozone is violent enough so that unprotected rubber is attacked even by low (rural) levels of ozone. The susceptibility of rubber to ozone attack created a situation that made it imperative to solve the problem in order to use economically any rubber products. A concentrated research effort identified the problem, developed measurement techniques and theoretical descriptions, and discovered prevention methods. The case of ozone and rubber might be studied for the purpose of modeling future research efforts along similar lines. The articles collected under this program in the category rubber/ozone include reviews and papers that describe cracking mechanisms, crack growth rate vs. ozone levels, and instrumentation. Literature devoted to additives and preventive chemistry was not collected or studied for this project. The vast majority of research effort is recorded in patents and company reports, which were not obtained for this study.

The field of plastics has been an area where the commercial products and consumer goods are constantly being produced at the state-of-the-art level. Many different formulations and additives which may change the chemistry of plastics are possible. These two facts mean that a producer of plastics does not really have time to test a sample to real exposure conditions prior to use, and is reluctant to report any shortcomings--especially when the loss is less than 10 percent of the expected lifetime. Thus plastic products are sold and used before exposure tests are made, and when exposure tests are completed, the plastics (especially those that show significant deterioration) are often obsolete. The literature reflects these problems; consequently, there are few articles concerning air pollution damage to plastics. The published exposure tests, D. V. Rosato, Ed., Environmental Effects on Polymeric Materials (Interscience Publishers, N. Y., 1968), and M. R. Kamal, Weatherability of Plastic Materials (John Wiley and Sons, N. Y., 1967), concern various climatic conditions with no regard to pollution level.

Fibers

As with most other nonmetals, there has been no concentrated research program to determine the effect of air pollution on fibers. The deterioration of cotton (which may have a normal rural lifetime of 13 months for outdoor exposure reduced to one month in an industrial environment) and nylon (a nylon stocking may last 6 days instead of 10 days due to air pollution) has been studied because results can be obtained in a reasonable period of time without accelerated tests. However, the mechanism of attack is not really understood because of the complexity of the molecules. Most of the available studies were performed in isolated laboratories; the results are frequently uncoordinated and difficult to interpret.

Damage to other fibers has received little attention; consequently, it is not well understood.

Finishes and Coatings

The available data in the literature cannot be used confidently to estimate a real value of economic loss due to pollutants because of the continual evaluation of new finishes and coatings.

Finishes and coatings comprise an extremely complex class of materials. These materials are "finish" or protective "coatings," and hence, severely subjected to the effects of the environment. This problem has received a great deal of research time, money, and effort. The ASTM exposure tests for finishes and coatings were performed in much the same manner as the exposure tests for metals, but were unsuccessful. This lack of success is due mainly to the fact that the endurance of a coating may be a function of the substrate, and that the coating can have an infinite variety of formulations (as in the case of plastics).

Many pollutants, principally H_2S, SO_x, O_3, NO_x, and metal particulates, damage some paints. The paint industry changes the chemical composition of the paints to prevent damage; however, this does not solve the problem because a new formulation is then subject to another unknown form of attack. One way to improve the research in this area is to improve the existing accelerated testing methods.

Other Materials

What little literature exists under this category concerns the effects of SO_x on paper and leather, and the effects of oxidants on asphalts. These articles, however, are not especially helpful in determining the actual damage incurred by these materials. The articles dealing with effects of SO_x on paper and leather are primarily the observations by librarians that paper and leather book bindings are becoming brittle prematurely. This observation has resulted in specifications for better ventilation and heating systems in libraries where valuable books are kept, but has not contributed toward a better understanding of the deterioration problem.

Literature Summary

For most materials with a few exceptions, notably wood, wool, concrete, and most plastics, there are at least qualitative reports of damage caused by air pollution in general, and qualitative correlations identifying either SO_x or O_3 as the causative agent. The only materials for which quantitative data exist are metals, rubber, and cotton. As for direct quantitative correlations of damage with a specific pollutant (dosage-response relationships), these exist only for zinc and SO_2, several varieties of rubber and O_3, and cotton and SO_2. Although most researchers agree that Cl^- and SO_2 are the major agents for increased corrosion of steel, a valid analytical dosage-response relationship is yet to be found.

The reader is referred to other recent literature reviews on the effects of air pollution on materials: Air Pollution, 2nd edition, Vol. 1, A. C. Stern (ed.), Academic Press, New York, 1968 (Effects on Materials, Ch. 15 by J. E. Yocum and R. O. McCaldin), a general review; Air Quality Criteria for Sulfur Oxides, Public Health Services (1969), Ch. 4, a review of destructuve effects of SO_x on materials; "Air Pollution Aspects of Metals and Their Compounds," Washington Technical Center, U. S. Public Health Service, Rept. PH 22-68-25 (1968), a review of the effects of 12 different metallic contaminants in the atmosphere; and H. C. Muffley, "Influence of Atmospheric Contaminants on Corrosion," Dept. of Army, Rept. No. 63-2041 (1963), a literature review of atmospheric corrosion.

Distribution of Literature in Comparison With Economic Rank Ordering

It is interesting to compare the distribution of the literature as a function of our estimated economic loss ranking. This is done in Table XV. The result of such a comparison in a perfect world--a world in which a study such as this would be unnecessary--would be that the maximum amount of research effort would have been given to the material ranked at the top and the least amount of effort given to the materials ranked on the bottom. The reason for this is simply that those materials that suffer the greatest, and consequently the most noticeable, damage should be given the most effort toward solution of the problem.

TABLE XV

SUMMARY OF LITERATURE QUALITY

Rank	Material	Number of Citations	Number of Citations Containing Useful Data	Quality of Information[a/]
1	Paint	35	11	GQl-PQt N.A.
2	Zinc	41	27	EQl-EQt
3	Cement and concrete materials	5	0	
4	Nickel	14	10	GQl-EQt
5	Cotton (fiber)	18	13	EQl-GQt
6	Tin	3	2	FQt
7	Synthetic rubber	26	17	EQl-EQt N.A.
8	Aluminum	32	19	GQl-EQt
9	Copper	21	17	EQl-EQt
10	Wool (fiber)	1	0	
11	Natural rubber	16	11	EQl-GQt
12	Carbon steel	26	13	EQl-FQt
13	Nylon (fiber)	9	4	GQl-PQt
14	Cellulose ester (fiber)	3	1	
15	Building brick	3	1	
16	Urea and melamine (plastic)	2	1	
17	Paper	5	2	PQl
18	Leather	4	1	PQl N.A.
19	Phenolics (plastic)	4	2	
20	Wood	3	0	
21	Building stone	16	3	GQl-PQt N.A.
22	PVC (plastic)	5	4	GQl N.A.
23	Brass and Bronze	10	9	GQl-GQt
24	Polyesters (plastic)	3	1	
25	Rayons (fiber)	2	1	
26	Magnesium	10	9	GQl-FQt
27	Polyethylene (plastic)	8	5	GQl-PQt
28	Acrylics (plastic)	1	1	
29	Alloy steel	38	18	EQl-EQt
30	Polystyrene (plastic)	8	5	
31	Acrylics (fiber)	0	0	
32	Acetate (fiber)	2	1	
33	Polyesters (fiber)	1	1	
34	Polypropylene (plastic)	2	1	
35	ABS (plastic)	2	1	
36	Epoxies (plastic)	4	3	
37	Cellulosics (plastic)	3	2	
38	Bituminous materials	1	1	
39	Gray iron	10	4	EQl-EQt
40	Nylons (plastic)	1	1	
41	Polyolefins (fiber)	0	0	
42	Stainless steel	5	0	
43	Clay pipe	0	0	
44	Acetate (plastic)	0	0	
45	Malleable iron	3	1	
46	Chromium	2	2	
47	Silver	10	5	EQl-EQt
48	Gold	5	4	
49	Flat glass	0	0	
50	Lead	8	5	EQl-EQt
51	Molybdenum	4	3	
52	Refractory ceramics	0	0	
53	Carbon and graphite	0	0	

[a/] Information has been judged in a very coarse manner to show its approximate value.

Note: Explanation of abbreviations:

E = Excellent	P = Poor	N.A. = Quantitative information available is not applicable in calculating economic loss.
G = Good	Ql = Qualitative information	
F = Fair	Qt = Quantitative information	

Materials with few or no articles warranted no comment.

Obviously, we do not expect perfect correlation between number of articles and economic loss ranking. Nonetheless, it is interesting to note that the 20 top-ranked materials were mentioned in an average of 14 articles each, whereas the last 20 were only mentioned in an average of three articles each. This gives us confidence in the ranking, which says, in effect, that this study has identified as economically significant material-pollutant combinations those which researchers have chosen to work with in the past. The correlation also permits identification of gaps in the research effort for materials such as concrete, which is ranked 3rd, but has received no significant mention in the literature. We also see that although a considerable amount of effort has been spent studying the effect of air pollutants on silver (principally tarnish by sulfur compounds), there is no real economic justification for such effort.

Trends in Air Pollution and Materials Usage

Besides being concerned about those materials which are currently being damaged by air pollution, and those pollutants currently responsible for the major portion of damage, it is also necessary to be aware of what will be the problems in the future.

As a society evolves, the pollutants in the atmosphere and the materials in use change. One might study cities such as Pittsburgh, Pennsylvania, and Los Angeles, California, to gain perspective. Until the late 1960's, the major air pollution problem in Pittsburgh was soot and tarry particulates caused by the almost sole dependence upon coal and fuel oils for fuels. The use of coal and heavy oils has since been almost eliminated, and the primary fuel is now natural gas. This has greatly changed the nature of the pollution, reducing the level of particulates by a factor of 3 or 4. Los Angeles is several years ahead of most other cities in cleaning up its industrial sources of air pollution. Consequently, solid particulates have been reduced to a small percentage (in terms of annoyance) of the total pollution problem. In Los Angeles, the pollution problem is primarily due to oxidants and hydrocarbons.

The quality of the air of many cities has evolved according to the following pattern. Initially the area is nonindustrialized, the population is small, and the air is clean. Industry moves in creating jobs and leading to population increases. Because no one has been harmed by foul air yet, air pollution control or regulation is lax or nonexistent, and the air becomes heavily polluted by solid and liquid particulates and gaseous pollutants. Since particulates and the damage caused by them (soiling) are most noticeable, the first air pollution control efforts go toward removing only the particulates. Removing the most offensive particulates will leave SO_2 from the burning of industrial fuels as the next largest problem. When this becomes noticeable through increased corrosion and irritation, efforts will be made to eliminate its presence by switching to natural gas as the primary fuel. The elimination of the major solid particulate (soot), reduction of SO_2, and the simultaneous growth of population will cause the major pollutants to be oxidants (O_3, NO_x, PAN, etc.). This is approximately the state in which the more advanced cities (in the sense of air quality) are now finding themselves.

It is not easy to predict the next steps in air pollution evolution, but at least there are possibilities that may be suggested: (a) Complete elimination of fossil fuels including natural gas, and switching to atomic energy sources with its presently unknown air pollution problems (possibly it will be radioactive tritium which will be much more harmful to living matter than to the materials defined in this study); (b) increased use of PVC plastics which cause the liberation of HCl when burned (in the process of disposal); this may cause chloride corrosion to be the predominant problem; (c) increased use of fertilizers will cause new problems, possibly the liberation of NH_3 which is highly corrosive.

While the quality of air is changing as old problems are solved and new ones are created, design engineers and materials designers work to insure satisfactory performance for materials exposed to this changing atmosphere. Thus, when synthetic rubber came into widespread use during the 1940's it became necessary to find additives which would prevent ozone cracking by prevailing levels of ozone. As the oxidant level in the atmospheres of cities increased, the amount and quality of the additives also had to be increased.

The chemical attack of most materials by pollutants can, by careful though perhaps costly design, be circumvented. The damage caused by soiling is easier (and perhaps much less costly) to reduce by reduction of particulate levels.

The introduction of new materials to withstand the rigors of a polluted environment will always lag behind the buildup of corrosive substances in the atmosphere. This is so because most effects of air pollution are sufficiently slight that they may not be recognized for 10 to 20 years. This situation could be greatly improved by valid accelerated testing methods.

Least understood of all are the effects of air pollution on nonmetallic materials. This lack of knowledge becomes more serious when it is realized that : (a) many nonmetallic products, especially those made of plastic, are designed almost to the limit of their physical properties; and (b) the use of nonmetallic materials is becoming increasingly important, and may soon become the major construction material.

In conclusion, if the major pollutants become oxidants as expected, and if the use of nonmetallic materials--especially plastics, sealants, adhesives and the composites, which are especially susceptible to attack by oxidants--become more prevalent, damage to these materials by air pollution will increase. Such increased damage may be prevented by either costly research for better materials or by elimination of air pollution.

CHAPTER X

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

Four major conclusions may be drawn from this study.

1. While it has been known for some time that materials are damaged by the action of air pollutants, information on the exact mechanisms and rates of attack is available only for a small number of specific material-pollutant combinations, notably zinc-SO_2, cotton-SO_2, and rubber-O_3.

2. In spite of the paucity of information, it is possible to estimate the economic losses caused by air pollution. In order to maintain all materials as clean as they would be in the absence of air pollution would require the expenditure of an estimated $100 billion per year. The direct economic losses caused by deterioration are estimated to be as high as $9.5 billion per year.

3. Soiling of paint, zinc, and flat glass (all used primarily as outdoor-exposed surfaces of buildings) is the cause of the major portion of economic loss.

4. In order to make further progress in the assessment of air pollution damage to materials, research is needed to obtain precise data on both physical-chemical and economic aspects of significant material-pollutant interactions. There is also a need for evaluation of the procedures used to obtain such data.

Each of these points is discussed in more detail below.

Interaction of Air Pollutants and Materials

In the past 50 years there have been only about 300 papers or reports dealing with the effects of air pollution on materials. Fewer than 100 of these present results of scientific experiments, and most of the experimentation has focused on either metals or rubber. Numerical values for the corrosion rates of metals cannot be correlated at high confidence levels to specific pollutants. The cases of accelerated corrosion of zinc exposed to SO_2 and ozone cracking of rubber are the only instances in which a positive quantitative correlation of material damage attributable to the concentration of a specific pollutant has been made.

Certainly, there are many cases of pollutant-material interactions which have been well documented with descriptive evidence--for example, damage to: paint by H_2S, SO_2, iron particles, and solid particulates; cotton and nylon (fibers) by SO_2; paper and leather by SO_2; and building stone by SO_2 and solid particulates. What is lacking, however, is sufficient quantitative information to allow accurate predictions of an attack rate as a function of pollutant concentration (dosage-response relationship).

Estimates of Economic Losses

Estimates have been made of the economic losses which are incurred as a result of the attack on materials by air pollution. These estimates were based on the total dollar value of the 53 most important materials, combined with estimates of the fraction of each material exposed to air pollution and the interaction rates for deterioration and soiling in a "polluted" atmosphere. Due to the uncertainty in the fractions exposed (derived from usage weighting factors) and interaction rates, the economic losses given have an expected error spread of a factor of 10. The ranking which results, though, is reasonably accurate in terms of order of economic significance.

The soiling of paint, zinc and flat glass accounts for 80 percent of all damage caused by suspended particulates. It was estimated that to eliminate the effects of suspended particulates would require an annual expenditure of $100 billion. Because the actual amount spent on cleaning is far less than this, it is evident that our urban areas are dirty and will remain so until the pollution level is substantially reduced.

Of the materials considered, paint, zinc, concrete and fibers suffer about 70 percent of the estimated loss due to deterioration. The economic loss suffered by 40 percent of all materials was estimated to be $3.8 billion. If it is assumed that the rest of the materials exhibit similar susceptibility to deterioration, the total is about $9.5 billion. Even if this value is in error by the maximum allowed by our estimated error (x 3), it would still imply a $3.1 billion annual loss. Recognizing that second order effects were not considered in this study, $9.5 billion appears to be a reasonable value.

Major Cause of Loss

One of the most significant conclusions of this study is that by far the greatest cause of damage is the soiling of materials by solid particulates. From the point of view of economics, the major effort at this time should be directed toward reducing suspended particulate levels.

Information Gaps

More substantial quantitative data are needed to refine this study and thereby strengthen economic justification for setting air pollution control standards and for implementing control regulations. Additional data are needed on both the physical-chemical and economic aspects of significant material-pollutant combinations. For the precise assessment of economic damage, input data in three major areas are required:

1. Materials: in-place value distributions in time and space, specifying the ratio of effective exposed surface area to volume.

2. Pollutants: intensity distributions (along with intensities of active climatological factors) in time and space (both open and closed).

3. Dosage-Response Relationships: mathematical formulations of the increased rates of chemical-physical deterioration of materials exposed to air pollution.

Materials for study should be given priority based on their economic significance and on the extent of pertinent knowledge. The most serious knowledge gaps in this field relate to concrete, paint, fibers, and plastics in approximately that order of economic significance. The effects of air pollution on plastics will probably become most significant as the use of plastics in building construction increases in the near future.

The pollutants which seem to be most effective in causing damage are: solid particulates, SO_2, and O_3, in that order. There are serious gaps in knowledge of the nature of soiling. Mechanisms and rates of soiling (as a function of the characteristics of both pollutants and receptor materials) are not well understood nor are the methods and standards by which "soiling" is measured.

There are three very basic problems which must be overcome in order for future tests and experiments to be used to advantage. These concern: data standards, low-concentration physical-chemical attack mechanisms, and accelerated testing techniques. Standards for reporting data should be established immediately in order that all future results may be coordinated. Until the physical-chemical reactions at low concentrations (< 1 ppm) are understood there will be little hope of completing useful pollutant-damage correlation studies. Basic research in this area, therefore, should be supported. The only hope of accumulating a reasonable amount of valid data in less than 16 years (the average lifetime of the materials considered in this study) is by developing adequate accelerated testing methods. This will require ingenuity and innovation. The accelerated testing methods currently used seldom correlate the life of the object to any environment other than that of the testing chamber.

RECOMMENDATIONS

These conclusions led us to recommend a fairly comprehensive research program which has the objective of filling in the information gaps discussed above. Due to the current state of the art in the field of the effects of air pollution on materials, this outlined research program is necessarily quite general. It seems reasonable to expect that the level of effort which should go into such a program should be about 1 percent of the estimated losses, which conservatively requires a budget of about $25-50 million per year.

A three-phase program is outlined. The objective of Phase I is to develop the capability to approach the problems at hand. This means promoting an interest in the subject, setting standards, and developing methods which will allow future research to progress in a fruitful manner. Phase II sets out to acquire the basic physical-chemical data which are needed. Phase III is designed to refine the systematic study of the effects of air pollution on materials and to insure that the results and efforts of the program remain up-to-date and meaningful.

Phase I Establish Approach and Methods of Attack

1. Centers of competence in corrosion research.
2. Standards for reporting air pollution data.
3. Dosage-response relationships.
4. Accelerated testing techniques.

Phase II Acquire Physical-Chemical Data

1. Soiling by particulate pollutants.
2. Corrosion studies.
3. Pollution effects on polymeric material.

Phase II Continuation and Refinement

1. Computer simulation of economic models.
2. Retrieval of damage complaint data.
3. Trends in air pollution and materials usage.
4. Analysis of legal cases involving air pollution damage.
5. Continued literature surveillance.

PHASE I

Centers of Research Competence

Universities and research centers should be funded to establish centers of competence and encourage the advance of basic knowledge in the field of material soiling and deterioration. Those which already exist should be supported.

Data Reporting Standards

Standards must be established for the reporting of all future soiling and deterioration data in order that they will be easily accessible to future researchers. We would propose following a format similar to that conceived by G.A. Nelson of Shell Development Company (see Corrosion, **25**(5), 233 (1969)). This format would, of course, have to be adjusted to be applicable to air pollutant concentrations.

Dosage-Response Relationships

The place of dosage-response relationships as definitive expressions of the effects of air pollutants on receptor materials has been reviewed earlier in this report. To date, attempts to develop such relationships, as reported in the literature, have been very limited; and, in most cases, they have been reduced to a simple correlation between the deterioration rate and some index of conditions of air pollution at the test locality.

It is recommended that experimentation first be conducted in a controlled environment for the purpose of developing explicit dosage-response relationships applicable over a wide range of imposed conditions.

Attention should be confined to a single receptor material, and the controlled environment should be representative of a normal atmosphere, except for containing only the one or two pollutants most damaging to the receptor material. At a later stage, correlative dosage-response relationships could be generated for natural environments (see Phase II below).

Since the state of knowledge is most advanced with respect to attack on metals, the first choice for a receptor material would be from this category. The material could be exposed as a thin film and concomitant analytical techniques could be developed so that this unaccelerated testing procedure could be carried out over a reasonable time scale.

One promising route for the determination of unaccelerated rate factors is through the development of high resolution techniques for surface examination. Such techniques would permit the investigator to measure the amount of damage after very short exposure times, possibly only a few hours. With this approach, the problem of time-concentration reciprocity would be eliminated and the observation would represent the real case.

Several recently developed techniques would lend themselves to the above study. Among these the most prominent are low-energy electron diffraction and Auger spectroscopy. These methods permit one to observe changes in only a few atoms on the surface of a material. It should, therefore, be possible to study pollution damage during the first hours of exposure and then to extrapolate to exposure times expected in real service.

It is anticipated that important basic knowledge would be obtained relative to the nature of dosage-response relationships, particularly in regard to the characterizing features of synergistic action among pollutants and climatological factors.

Accelerated Testing

Most laboratory testing of pollutant-material interactions has been of an accelerated nature. This is to be expected, since most materials have long life expectancies.

The major difficulties associated with accelerated testing stem from the fact that material deterioration in a polluted atmosphere is generally very complex, involving a combination of pollutants and climatological factors. One is faced with the imposing problem of increasing in the same proportion all of the factors active in each mode of deterioration. The situation is further complicated by interaction between the various deteriorative modes themselves. Results cannot be extrapolated back to realistic exposure conditions unless dependence on each active factor is mathematically simple.

Even though, for the reasons stated above, suspicion is cast on results from present "weatherometer" devices (AE-217), it is not likely that accelerated testing will be abandoned.

It is recommended that the literature be thoroughly reviewed to determine the state of knowledge of accelerated testing as characterized by the various experimental devices and methods in use, along with the associated mathematical techniques. It is further recommended that a systems analysis approach be employed to develop possible accelerated testing programs correlating results from controlled environment devices (as suggested in dosage-response relationships' section above) with simultaneous outdoor testing. Finally, one or more of the most promising programs should be subjected to intensive testing using a receptor material (say, a nonferrous metal) for which the mechanism of deterioration and the major active factors involved are reasonably well understood.

PHASE III

Soiling by Particulate Pollutants

Soiling by particulate pollutants appears to be a major cause of economic loss in an urban-industrial area--exceeding in cost the loss due to material attack by chemically active pollutants on all materials combined. Certainly, a major portion of the initial research effort should be directed towards this problem. At least three steps should be undertaken to accomplish this: (a) investigate the basic physics of particle-surface adhesion; (b) conduct studies which give soiling rates as a function of particle size and density for various receptor materials; and (c) consider alternatives.

Physics of particle-surface adhesion: At present little is known about the nature of the adhesion of particles to receptor surfaces. Studies of contact electrification of solids suggest that charge transfer between a particle and a surface can produce a strong binding force. Van der Waals' attractions are also known to produce very strong bonding energies. Some questions to be answered are: (1) what are the strengths of particle-surface bonds?; and (2) how do these depend on material properties?

Particle-surface interfacial energies are very difficult to measure quantitatively, but a new technique has been suggested which appears promising. Particles adhering to a ultrahigh speed rotor are spun off when the centrifugal force exceeds their binding force. From the spin-off velocity and particle mass the adhesion energy can be calculated. A systematic variation of the properties of both the rotor material and particles should quickly provide a great deal of insight into the basic mechanism of particle-surface adhesion and soiling.

Soiling rates: Studies should be conducted both in controlled and natural environments to obtain the soiling rates as a function of particle size and density, meteorological conditions, and properties of the receptor material. One of the first steps would be to establish means of objectively and quantitatively measuring the state of "soiling." Soiling rates must be found for all significant materials.

The results of these studies could be used to improve the reliability of the estimates we have made in this study. Knowledge of the effect of particle size on soiling may permit reduction of dinginess by a much greater factor with less effort, if, for example, it is found that a particular size range is responsible for the majority of the soiling.

Alternatives: The soiling problem is being attacked by attempts to eliminate particulate emissions. However, effective elimination of particulate emissions may impose too severe an economic penalty on an industry, so that the cost of control offsets the savings.

Alternative means of lowering the economic loss due to soiling should be investigated. A better understanding of the mechanisms of soiling may suggest: (1) new ways of protecting surfaces from soiling; (2) inexpensive ways of modifying particulate emissions so as to reduce their soiling effect; or (3) less expensive ways of cleaning soiled surfaces.

Corrosion Studies

Outdoor exposure tests such as those conducted in the past under the direction of the ASTM must be continued. However, new tests should be designed to generate dosage-response relationships as discussed earlier. This means that more care must be given to recording ambient pollutant concentrations.

These studies should then be continued in order to insure that data will be available for newly formulated alloys. Also, changing trends in air pollution quality will make past results inapplicable.

The ASTM and certain metals companies already have many exposure test samples out, but do not have sufficient funds to retrieve them. These projects should be funded in preference to establishing new exposure tests.

Pollution Effects on Polymeric Materials

Much of the material falling under the general heading of "polymeric" is used for short-lived packaging, and the economic effects of pollution on them seems to be of limited importance. Polyethylene and polypropylene are examples of such materials. On the other hand, the degradation of the polymers which are used in construction has considerable economic significance and deserves further investigation.

The construction and automotive industries are using steadily increasing amounts of polymers such as acrylic glazing, glass, reinforced panels, and ABS plumbing. These materials, already accounting for extensive financial investment, promise to grow considerably in use. The potential economic effect of pollution on them appears great.

It is difficult to suggest a course of experimental study for this problem area because exposure and effect data are scarce in the literature. Furthermore, accelerated experiments would be of little value before real-time studies were made and degradation standards established.

The first step toward evaluation and eventual treatment of the problem of pollution damage to the construction polymers should be a survey of the industry from manufacturers to builders and maintenance departments. This survey should be designed to: (1) delineate the types of problems associated with pollution damage; (2) improve the estimate of costs involved; (3) determine the ability and willingness of the various industrial segments to contribute to a real-time effects program; and (4) to select those areas where either accelerated exposure tests or highly sensitive real-time tests could be effective.

In the first aim of such a survey it is to be recognized that much of the pollution damage to polymers in construction may be aesthetic rather than structural. Therefore, the costs of such damage must include cleaning and restoration costs. The complications introduced into this effort by local variations in cleaning habits and material color preferences will make it a difficult task and will necessitate sophisticated data analysis. Nevertheless, there seems to be no other practical starting point in the area of pollution effects on polymers used in construction.

The need for real-time exposure data obviously cannot be met in the immediate future without the aid of those users whose accumulated knowledge can be made available. Our own experience in various fields suggests that many outside agencies would cooperate in an information exchange in return for summarized reports on such a project. We expect that about one year would be needed for the survey and the selection of areas for advance study. Laboratory work would not be fruitful until the problem is more clearly defined through such a survey and analysis.

PHASE III

Computer Simulation of Economic Models

Once dosage-response relationships have been developed to provide accurate descriptions of the real world, computer simulation of material-pollutant interactions as part of an economic model of an entire urban-industrial area would be feasible. Computer simulation may be performed at almost any level of complexity depending upon the amount of real data which is available.

As a beginning, it may be desirable to use computer simulation to compute the life expectancy of a single item composed of one material as a function of pollutant concentrations and other environmental conditions--humidity, temperature cycle, wind and other climatic conditions.

The next step would be to compute the life expectancy of composite objects, assuming the behavior of each of its components is known.

The ultimate objective would be to construct a model of an entire urban-industrial area of, for example, a population of 500,000. All pollutant sources would be identified as well as the distribution of materials. Given any meteorological conditions the pollution concentration could be computed as a function of location. Dosage-response relationships would be used to compute the incremental loss. The whole process would be iterated for the length of time required for adequate statistics. The final results could be compared with real life by a survey of a similar real city, and parameters would then be adjusted to give a more accurate description of the real world.

Similar computer simulation is already in existence, up to the point of computing pollution densities as a function of time, location, source intensities, and meteorological conditions. What is now required are accurate dosage-response relationships.

Retrieval of Damage Complaint Data

Both the Los Angeles and the San Francisco Bay Area air pollution control districts (and presumably most others) handle damage complaints. Approximately 10 percent of total complaints (about 1,500 total in each of these areas) are concerned with property damage. These complaints could provide valuable statistical data if the file system were altered to permit retrieval and use of this information. At present this is impossible, mostly due to lack of funds. The San Francisco APCD has suggested that such a file system could be set up at a cost of no more than one-half of a secretarial salary per year. This would be an inexpensive means of generating damage statistics. It would also tend to keep the moods and cares of the people in mind, by indicating what people are willing or unwilling to accept in the way of polluted air.

Trends in Air Pollution and Materials Usage

This research program has dealt with the economic effects of currently prevailing air pollutants on existing materials. However, the situation with regard to both pollutants and materials is constantly changing, and the effects of these changes should be carefully considered in all future research.

Analysis of Legal Cases Involving Air Pollution Damage

Court awards for property damage due to air pollution have been almost nil in the past. With the population becoming more aware of air pollution, it seems likely that in the near future there will be more lawsuits in which a local pollution source will be sued for property damages, and equally likely that damages will be awarded. Some effort should be spent in maintaining contact with court cases as a means of estimating the amount of air pollution damage.

Continued Literature Surveillance on Economic Effects

A final, obvious recommendation, included only for completeness, is that there be continued literature surveillance on the economic effects of air pollution on materials.

The extensive bibliography contained in the Appendix to this report covers virtually all significant published work dealing with the economic effects of air pollution on materials. As such, it provides an excellent data base for future research in the area of economic effects. It should not be allowed to become outdated.

Surveillance of new literature pertaining to economic effects research should be continued to maintain the information system in current order. For the amount of literature currently available, the McBee Keysort information retrieval system developed in the current project and described in Chapter III of this report would be adequate. One person, on a full-time basis, could maintain the economic effects information systems, and prepare brief abstracts and evaluations of new contributions to the literature.

APPENDIX A

DISTRIBUTION OF LITERATURE ON EFFECTS OF AIR POLLUTION ON MATERIALS

DISTRIBUTION OF LITERATURE ON EFFECTS OF AIR POLLUTION ON MATERIALS

Each piece of literature was read and classified according to the material-pollutant combination(s) discussed. Table A-1 shows the result of this effort. The numbers given have the following meaning.

AE-XXX - designates a particular article

BE-XX - " " " book,

where AE-XXX and BE-XX are accession numbers (chronological order of acquisition) and correspond to the Accession Bibliography given in Appendix C.

Any reference which is specifically about one material-pollutant combination or which contains original and useful data or discussion of the effects of pollutants on materials has been given an asterisk, i.e., AE-XXX.* Unstarred references are vague, general and/or reviews. However, since this is a rating peculiar to the particular objective of finding quantitative data on effects, it does not mean that there is no pertinent information in the unstarred listings.

A reference is listed opposite a material and under "Gen." if no correlation was made between the damage observed and a specific pollutant.

The major objective of this classification is to give the reader a quick evaluation of the distribution of previous research effort in the area of effects of air pollution on materials.

TABLE [illegible]-1

DISTRIBUTION OF LITERATURE ON EFFECTS OF AIR POLLUTION ON MATERIALS

	Gen.		Organic	NO_x	SO_x		O_3	CO_x, NH_3, HCl, H_2S	Part.
100.00 Ferrous Metals	AE-231	AE-175	AE-162		AE-189*	AE-20		AE-331*	AE-33*
	AE-270	AE-182			AE-34*			AE-332*	AE-143*
	BE-3	AE-15			AE-192			AE-264	AE-273
	BE-4*	AE-16			AE-10			AE-64*	AE-284
	AE-1[illegible]	AE-14			AE-284			AE-113	AE-264
	AE-1[illegible]	AE-90*			AE-264				AE-113
	AE-9*	AE-108			AE-64*				AE-288
	AE-312	AE-69			AE-151				
	AE-313	BE-14*			AE-113				
		BE-15*							
101.00 Gray Iron	AE-45		AE-297		AE-283*			AE-42*	AE-42*
	AE-111*				AE-101*			AE-138	
	AE-77				AE-42*				
	AE-76								
	AE-105								
102.00 Malleable Iron	AE-105				AE-139*			AE-138	
103.00 Alloy Steel	AE-301*	AE-62	AE-27		AE-308	AE-170		AE-308	AE-272*
	AE-298*	AE-52*			BE-7*	AE-183		AE-70	AE-133
	AE-74*	AE-13*			AE-150	AE-130		AE-116	AE-163
	AE-111*	AE-133			AE-166	AE-133		AE-117*	AE-154*
	AE-190	AE-105			AE-283*	AE-26*		AE-185	
	BE-7*	AE-26*			AE-226	AE-243*		AE-99	
	BE-6*	AE-110*			AE-272*	AE-163		AE-183	
	AE-100*	AE-243*			AE-268	AE-220*		AE-29	
	AE-197	AE-154*			AE-99	AE-309		AE-138	
	AE-184	AE-316*						AE-309	
104.00 Carbon Steel	AE-74*	AE-133			AE-150	AE-42*		AE-117*	AE-272*
	AE-111*	AE-105			AE-166	AE-146		AE-185	AE-133
	BE-7*	AE-26*			AE-272*	AE-13*		AE-99	AE-42*
	BE-6*	AE-243*			AE-99	AE-26*		AE-42*	AE-163
	AE-100*				AE-170	AE-243*		AE-138	
	AE-184				AE-130	AE-163			
	AE-62				AE-133	AE-220*			
	AE-52*								

TABLE A-I (Continued)

	Gen.		Organic	NO_x	SO_x	O_3	Other Inor.	Part.
105.00 Stainless Steel	AE-79 BE-7 AE-136				AE-308	AE-277	AE-308	
200.00 Nonferrous Metals	AE-175 AE-231 BE-3 BE-4* AE-135 AE-173	AE-15 AE-16 AE-14 AE-90* AE-108 AE-69 AE-109* BE-14* BE-15*	AE-94 AE-54 AE-134* AE-188* BE-5* AE-329		AE-264 AE-151 AE-113 AE-94		AE-264 AE-113 AE-94 AE-329	AE-143* AE-273 AE-264 AE-113 AE-288 AE-325 AE-329
201.00 Aluminum	AE-148* AE-74* AE-190 BE-7* AE-79 AE-136 AE-76* AE-26* AE-246 AE-53*	AE-168* AE-180* AE-181 AE-179* AE-169* AE-167 AE-125* BE-6* AE-315* AE-316*	AE-297		AE-308 AE-150 AE-166 AE-70 AE-272* AE-101* AE-64* AE-26* AE-109* AE-131*	AE-277	AE-308 BE-6 AE-64* AE-107 AE-181	AE-272*
202.00 Brass and Bronze	AE-76* AE-26* AE-110* AE-124	AE-169* AE-167* AE-137*		AE-248*	AE-64* AE-26*	AE-248*	AE-64* AE-248*	AE-178*
203.00 Chromium	AE-76*	AE-161*						

(3)

TABLE A-I (Continued)

	Gen.		Organic	NO_x	SO_x		O_3	Other Inor.	Part.
204.00 Copper	AE-74* AE-79 AE-76* AE-110* AE-169* AE-167* AE-316*	AE-125* AE-48* AE-55* AE-39* AE-153* BE-6*	AE-297	AE-8*	AE-308 AE-284 AE-59*	AE-59* AE-37* AE-8* AE-144*		AE-308 AE-109* AE-59 AE-39* AE-8* AE-144*	AE-284 AE-153*
205.00 Gold	AE-226	AE-153*	AE-54*		AE-8*	AE-144*		AE-8*,AE-144*	AE-153*
206.00 Magnesium	AE-74* AE-76* AE-169* AE-167*	AE-125* AE-66* AE-198* BE-6*	AE-297		AE-109* AE-66*			BE-6 AE-109* AE-66*	
207.00 Molybdenum	AE-169* AE-167*	AE-125*	AE-297						
208.00 Lead	AE-74* AE-79 AE-76*	AE-169* AE-167* AE-125*	AE-297		AE-284				AE-284
209.00 Nickel	BE-7 AE-76* AE-110* AE-169*	AE-167* AE-125* AE-278*	AE-297		AE-308 AE-150 AE-101* AE-109*	AE-12* AE-59*		AE-308 AE-109* AE-12* AE-59*	
211.00 Tin	AE-76*		AE-297	AE-8*	AE-8*		AE-8*	AE-8*	
210.00 Silver	AE-226 AE-79	AE-76* AE-153*	AE-297 AE-54*	AE-8*	AE-61 AE-8*	AE-144*	AE-61 AE-8*	AE-163 AE-61 AE-8* AE-144*	AE-153*

TABLE A-I (Continued)

	Gen.		Organic	NO$_x$	SO$_x$		O$_3$	Other Inor.	Part.	
212.00 Zinc	AE-74* AE-190 BE-7* AE-62 AE-52* AE-13* AE-76* AE-26* AE-110* AE-243* AE-246 AE-169*	AE-167* AE-125* AE-269* AE-202 BE-8* AE-49* AE-187* AE-67* AE-211* AE-149* AE-154 AE-316*	AE-297		1 BE-7* AE-150 AE-166* AE-272* AE-99 AE-170 AE-101* AE-146	AE-284 AE-64* AE-26* AE-243* AE-20 AE-163 AE-107* AE-186*		AE-99 AE-64* AE-109*	AE-272* AE-284 AE-163 AE-178 AE-49* AE-154*	
300.00 Stone, Clay, Glass	AE-231 AE-108 AE-69 AE-128 BE-12				AE-264 AE-140 AE-260			AE-264	AE-273 AE-264 AE-288 AE-223* AE-274 AE-122*	AE-5* AE-6* AE-7* AE-36 AE-285
301.00 Building Stone	AE-260 AE-124 AE-41 AE-114 AE-320				AE-284 AE-151 AE-244* AE-115 AE-228*	AE-46 AE-281*		AE-244* AE-115 AE-46	AE-284 AE-288 AE-244* AE-115 AE-228	
303.00 Building Brick					AE-284 AE-46	AE-281*		AE-46	AE-284	
306.00 Cement and Concrete	AE-260	AE-118			AE-284 AE-151	AE-46		AE-46	AE-284	
309.00 Nonrefract. Ceramics	AE-324								AE-324	

BLE A-I (Continued) (5)

	Gen.	Organic	NO_x	SO_x	O_3	Other Inor.	Part.
310.00 Glass							
312.00 Carbon and Graphite							
400.00 Plastics and Rubber	AE-90* BE-16* AE-108 BE-19 AE-216 AE-320 BE-9 AE-158 BE-12 BE-13 AE-282	AE 262* AE-256* AE-249*	AE-262* AE-256* AE-249* AE-310	AE-310	AE-255 AE-259 AE-253 AE-252 AE-245 AE-257* AE-266 AE-256* AE-262* AE-249* AE-261 AE-156 AE-158 AE-310 AE-265		
470.00 Synthetic Rubber	AE-210* AE-237		AE-155 AE-35* AE-216		AE-224* AE-276 AE-239* AE-58* AE-238* AE-233* AE-235* AE-30 AE-176* AE-222* AE-80* AE-247* AE-177* AE-240* AE-159* AE-155 BE-2* AE-35* AE-225 AE-216 AE-234 AE-235 AE-267* AE-322		
401.00 Natural Rubber			AE-35* AE-155		AE-163 AE-80* AE-247* AE-177* AE-222* AE-176* AE-30 AE-232 AE-58* AE-224* AE-225 AE-241* BE-2* AE-159*		

(6)

TABLE A-I (Continued)

	Gen.		Organic	NO_x	SO_x	O_3	Other Inorg.	Part.
421.00 Polyethylene	AE-305* AE-304*	AE-147 AE-317*		AE-214* AE-215*		AE-277		AE-104
425.00 Polystyrene	AE-216	AE-89*		AE-216 AE-119* AE-330	AE-330	AE-216 AE-160* AE-318*		AE-104
426.00 PVC	AE-305* AE-304*	AE-89*	AE-321*		AE-302*	AE-302 AE-277		
431.00 Phenolics	AE-296* AE-295*	AE-89						AE-104
422.00 Polypropylene			AE-321*					AE-104
432.00 Urea + Melamine	AE-295*							AE-104
433.00 Polyesters	AE-295*	AE-89						AE-104
428.00 Acrylics	AE-89*							
441.00 ABS	AE-147		AE-321*					
429.00 Cellulosics	AE-296* AE-295	AE-89*						

TABLE A-1 (Continued)

(7)

	Gen.		Organic	NO$_x$	SO$_x$		O$_3$	Other Inorg.	Part.	
451.00 Epoxies	AE-296* AE-295*	AE-216 AE-89*		AE-216			AE-216			
461.00 Acetate										
423.00 Nylons	AE-89*									
500.00 Fibers	AE-231 AE-260 AE-108 AE-128	AE-60 AE-88 AE-73 AE-227		AE-152*	AE-264 AE-151 AE-113	AE-115 AE-152*	AE-152* AE-97*	AE-264 AE-113	AE-273 AE-264 AE-113 AE-233 AE-274 AE-122 AE-115	AE-5* AE-6* AE-7* AE-36 AE-230 AE-91*
501.00 Cotton	AE-226 AE-275* AE-98 AE-17* AE-209 AE-50* AE-95* AE-19		AE-206	AE-20	AE-226 AE-20 AE-163* AE-17* AE-50*		AE-20 AE-207* AE-212* AE-97* AE-87* AE-103* AE-106* AE-156		AE-163 AE-98* AE-17* AE-50*	
511.00 Wool	AE-208									
521.00 Rayon				AE-196 AE-195*	AE-196 AE-195*					
542.00 Acetate				AE-86			AE-97*			
543.00 Acrylics										
531.00 Nylon	AE-226 AE-275*		AE-44*	AE-293 AE-44*	AE-226 AE-163	AE-293 AE-44*	AE-293 AE-97* AE-44* AE-156	AE-293	AE-84*	

ABLE A-I (Continued)

(a)

	Gen.			Organic	NO_x	SO_x		O_3	Other Inorg.	Part.
544.00 Polyester								AE-97*		
546.00 Polyolefins										
541.00 Cellulose Esters	AE-200				AE-86			AE-103*		
600.00 Finishes & Coatings	AE-175	AE-271*	AE-72*	AE-68	AE-196	AE-152		AE-196	AE-171	
	AE-231	AE-86*	AE-85		AE-152	AE-68		AE-152	AE-121*	
	AE-173	AE-195*	AE-56		AE-68	AE-171		AE-88*		
	AE-90	AE-88*	AE-71		AE-171	AE-121*		AE-68*		
	AE-108	AE-73	AE-102*		AE-77*			AE-171		
	AE-246	AE-68*	AE-164*		AE-78*			AE-78*		
	AE-124	AE-75*			AE-121*			AE-121*		
601.00 Paint	AE-226	AE-221	AE-142		AE-63	AE-302*	AE-191*	AE-302*	AE-264	AE-269
	AE-260	AE-141	AE-199		AE-157*	AE-220	AE-220*	AE-157*	AE-151	AE-288
	AE-69	AE-32	AE-311*			AE-226	AE-220*		AE-63	AE-285
	AE-217*	AE-22	AE-314			AE-264			AE-294*	AE-251
	AE-286	AE-203	AE-319			AE-151			AE-290*	AE-157*
	AE-254	AE-250	AE-323			AE-63			AE-21*	AE-28*
									AE-327	AE-31*
700.00 Other Materials	AE-90*		BE-13							
	AE-108		AE-282							
	AE-23									
	AE-126									
701.00 Wood	AE-205									AE-115
	AE-320									
711.00 Paper						AE-264			AE-264	AE-264
						AE-151			AE-113	AE-113
						AE-113				
						AE-120*				
						AE-25*				

TABLE A-I (Concluded)

(9)

	Gen.		Organic	NO$_x$	SO$_x$		O$_3$	Other Inor.	Part.
721.00 Leather					AE-264	AE-113		AE-264	AE-264
					AE-151	AE-92*		AE-113	AE-113
731.00 Bitum. Materials				AE-27*			AE-27*		
							AE-156		
Economic	AE-127	AE-194			AE-3				AE-1
	AE-307	BE-1			AE-1				
	AE-15	AE-292							
	AE-16	AE-291							
	AE-14	AE-4							
	AE-128	AE-225							
	AE-2	AE-227							
	AE-263	AE-128							
	AE-236	AE-94							
	AE-123	AE-192							
	AE-172	AE-173							
	AE-107	AE-273							
	AE-93	AE-105							
	AE-83	AE-14							
	AE-82	AE-15							
	AE-81	AE-16							
	AE-218	AE-307							
	AE-11	BE-17							
		BE-18							

APPENDIX B

BIBLIOGRAPHY

(Ordered by Class of Material)

This bibliography is ordered by classes of materials and the entries in each class are ordered alphabetically by author. No article is listed twice. An article which discussed topics in several classes of materials is listed only in the first class. If only the abstract is in our file, the notation Abs. follows the date. The number following the date is the article accession number.

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APPENDIX D

PERSONS CURRENTLY INVOLVED IN RESEARCH CLOSELY RELATED TO THE EFFECTS OF AIR POLLUTION ON MATERIALS

It was desired to generate a list of persons, currently active in research, whose talents could be utilized to study the effects of air pollution on materials. This list is composed of three subdivisions, each with its own merit.

1. ASTM Committee Chairmen

Since the ASTM has been actively engaged in testing and setting standards for materials, it is only logical to search their organization for men competent in the study of materials. A search was made of the ASTM Yearbook, 1969-70, and a list made of all committees and subcommittees, along with the chairman of each, which are directly involved with the testing of the durability, lastability, weathering, corrosion or deterioration of materials, especially out-of-doors or atmospheric testing.

These persons may not be directly involved with air pollution damages, and most of them certainly are not; however, their background and specialty makes it desirable to work in association with them when beginning a program closely related to this discipline.

2. Current Research

The Science Information Exchange searched their listing for all persons currently engaged in research on "The Effects of Air Pollution on Materials." The resulting list is composed of project leaders of projects funded for FY 1968, FY 1969, and/or FY 1970. Not all of these projects are still active. It is highly probable that there are also projects which are active but were not listed because they were never listed with SIE, and, therefore, do not occur here.

3. Recent Literature

All the authors of significant published articles or reports on the effects of air pollution on materials, which are dated 1967, 1968 or 1969 were collected to complete our listing. For articles of joint authorship, all the authors are listed. Authors of recent literature, who were already listed under "Current Research" above, were not listed again. Persons listed under "Current Research" or "Recent Literature" may also be listed under "ASTM Committee Chairman."

The following is a list of ASTM committees which are concerned with corrosion, weathering, durability, and testing of materials which are pertinent to the field of air pollution effects on materials. These committees were obtained from the ASTM Yearbook, 1969-70. The chairman of each committee and subcommittee is given, along with his organization.

Committee		Chairman	Organization
A-10	"Iron-Chromium-Nickel and Related Alloys."	R.B. Gunia	U.S. Steel Corp.
	Sub. Comm. IV, "Methods of Corrosion Testing."	M.H. Brown	Du Pont De Nemours
B-8	"Electro Deposited Metallic Coatings."	R.B. Saltonstall	The Udylite Corp.
C-9	"Concrete and Concrete Aggregates"	E.A. Whitehurst	Tenn. Highway Research Program
	Sub. Comm. III-o, "Methods of Testing Concrete for Resistance to Weathering."	H.H. Newlon, Jr.	Virginia Dept. of Highways
C-19	"Structural Sandwich Constructions."	E.W. Kuenzi	Forest Products Lab.
	Sub. Comm. III, "Permanence, Durability, and Simulated Service."	D.R. Miller	General Electric Co.
D-1	"Paint, Varnish, Lacquer, and Related Products."	J.C. Moore	Moore Research Labs. Inc.
	Sub. Comm. 27, "Accelerated Tests for Protective Coatings."	W.B. Bartelt	Rust-Oleum Corp.
	Sub. Comm. 44, "Traffic Paints."		
	Working group 2, "Accelerated Tests of,"	F.G. Flint	
D-6	"Paper and Paper Products."	T.W. Lashof	National Bureau of Standards
D-7	"Wood."	W.A. Oliver	University of Illinois
	Sub. Comm. XIII, "Durability and Exposure."	E.L. Schaffer	
D-11	"Rubber and Rubber-Like Materials."	G.C. Maassen	R.T. Vanderbilt Co.
	Sub. Comm. 15, "Life Tests."	R.T. Zimmerman	R.T. Vanderbilt Co.
	Sub. Section P, (SAE), "Static Exposure Tests."	M. Lowman	Goodyear Tire and Rubber Co.
D-13	"Textile Materials."	D.S. Hamby	North Carolina State University
D-14	"Adhesives."	W.E. St. Clair	Koppers Co. Inc.
	Sub. Comm. III, "Permanence Properties."	M. Petronio	Frankford Arsenal

D-20	"Plastics."	G.H. Williams, Jr.	Bell Telephone Lab., Inc.
	Sub. Comm. 50, "Permanence Properties."	E.J. Page	Belding Heminway Co., Inc.
E-9	"Fatigue."	H.F. Hardrath	NASA, Langley Research Center
	Sub. Comm. VIII, "Fatigue Under Cyclic Strain."		
	Task Force on "Influence of Environment."	D.W. Hoeppner	Battelle Memorial Inst.
E-12	"Appearance of Materials."	W.J. Kiernan	Bell Telephone Lab., Inc.
G-1	"Corrosion of Metals."	W.H. Ailor	Reynolds Metals Co.
	Sub. Comm. IV, "Atmospheric Corrosion."	S.K. Coburn	U.S. Steel Corp.
	Sub. Comm. VI, "Stress Corrosion Cracking & Corrosion Fatigue."	H.L. Craig, Jr.	Reynolds Metals Co.
G-3	"Deterioration of Non-Metallic Materials."	F.M. Gavan	Armstrong Cork Co.
	Sub. Comm. 3, "Simulated and Controlled Environmental Tests."	J.E. Clark	National Bureau of Standards
(ALCA and ASTM)	"Leather"	R. Stubbings	Milwaukee School of Engineering
Div. A-8	"Deterioration Effects."	E.M. Filachione	U.S. Dept. of Agriculture
Div. A-12	"Lastability."	R.J. Oris	Endicott Johnson Corp.

The following is a list of men and their associated organizations who are active in research on the effects of air pollution on materials. A brief description of their project accompanies each name. This list was obtained from Science Information Exchange, and covers the period fiscal years 1968-1970.

Project	Project Leader	Organization
Weathering of Building Materials	T.H. Boone	National Bureau of Standards Washington, D.C.
Weatherability of Plastics	J.E. Clark	National Bureau of Standards Washington, D.C.

Exposure of Building Materials	W.C. Cullen	National Bureau of Standards Washington, D.C.
Atmospheric Corrosion of Wire Products	A.C. Dale	Purdue University Lafayette, Indiana
Performances of Organic Coatings	R.B. Fox	Naval Research Lab., Washington, D.C.
Durability of Building Materials	V.E. Gray	National Bureau of Standards Washington, D.C.
Fatigue Simulated Environment	H.F. Hardrath	Langley Research Center Hampton, Virginia
Air Pollutants on Polymers	H.G. Jellinek	Clarkson College of Technology Potsdam, New York
Concrete Exposure	K.R. Lauer	University of Notre Dame Notre Dame, Indiana
Degradation of Cotton Fabrics	J.S. Lee	New Mexico State University University Park, New Mexico
SO_2 and Textile Fibers	R.M. Manganelli	Rutgers, the State University New Brunswick, New Jersey
Stress Corrosion of Structural Materials	E.E. Mathauser	Langley Research Center Hampton, Virginia
Ozone Effects on Aerospace Structures	E.P. Miller	AF Flight Dyanmics Laboratory AFFDL/FDTE/WPAFB
Air Pollutants on Textile Fabrics	M.A. Morris	University of California Davis, California
Atmospheric Exposure of Adhesives	R.H. Perkins	Purdue University Lafayette, Indiana
Atmospheric Corrosion of Metallic Composites	J.W. Pitts	National Bureau of Standards Washington, D.C.
Metal Corrosion from Atmospheric Pollution	H.G. Poertner	American Public Works Assoc. Chicago, Illinois

Stress-Corrosion Cracking	**E.N. Pugh**	**Martin Marietta Corporation** **Baltimore, Maryland**
Air Pollution on Fabrics	V.S. Salvin	University of North Carolina Greensboro, North Carolina
Effects of Air Pollution on Urban Form	B.H. Stevens	Regional Science Research Inst. Philadelphia, Pennsylvania
Economic Effects of Air Pollution	H.C. Wohlers	Drexel Institute of Technology Philadelphia, Pennsylvania

AUTHORS OF RECENT LITERATURE

Topic	Date	Author	Organization
Atmospheric exposure of light metals	1968	L.H. Adam	Frankford Arsenal Philadelphia, Pennsylvania
Performance of aluminum alloys at test sites	1968	W.H. Ailor, Jr.	Reynolds Metal Company Richmond, Virginia
Effects of air pollution on dyes	1967	R.L. Ajax	Nat'l. Center for Air Pollution Control Cincinnati, Ohio
Corrosion of mild steel in areas of Northern California	1968	H.N. Alderson	Pacific Gas and Electric Co. Emeryville, California
Effects of air pollution	1969	A.P. Altshuller	Nat'l. Air Pollution Control Administration Cincinnati, Ohio
Stress corrosion of titanium	1968	J.R. Ambrose	Nat'l. Bureau of Standards Washington, D.C.
Economic losses due to air pollution	1969	R.J. Anderson	Nat'l. Air Pol. Control Admin. Arlington, Virginia
Effects of ozone and electrostatics on cotton	1969	A. Baril	Southern Regional Res. Lab. U.S. Dept. of Agriculture New Orleans, Louisiana

Topic	Date	Author	Organization
Durability of building materials	1968	H.W. Berger	Nat'l. Air Pol. Control Admin. Cincinnati, Ohio
Atmospheric corrosion of stainless steel automotive trim	1968	H.L. Black	Cyclops Corporation Pittsburgh, Pennsylvania
Economical protection of steel against corrosion by paint	1969	W. Bosch	University of Missouri Rolla, Missouri
Predicting service life of coatings	1968	B.G. Brand	Battelle Memorial Institute Columbus, Ohio
Atmospheric exposure of light metals	1968	S.M. Brandt	Bohn Aluminum and Brass Co. Detroit, Michigan
Air pollution damage to cotton	1968	R.J. Brysson	Southern Regional Res. Lab. U.S. Dept. of Agriculture New Orleans, Louisiana
Effects of air pollution on materials	1967	J.H. Cavender	Nat'l. Center for Air Pol. Control Cincinnati, Ohio
Effects of air pollution on dyes	1967	C.J. Conlee	Univ. of Washington Seattle, Washington
Air pollution damage to cotton	1968	A.S. Cooper	Southern Regional Res. Lab. U.S. Dept. of Agriculture New Orleans, Louisiana
Atmospheric corrosion of nickel alloys	1968	H.R. Copson	Internat'l. Nickel Co., Inc. Sterling Forest, Suffern, N.Y.
Atmospheric stress corrosion testing of aluminum	1968	H.L. Craig, Jr.	Reynolds Metals Co. Richmond, Virginia
Economic losses due to air pollution	1969	T.D. Crocker	Univ. of Wisconsin Milwaukee, Wisconsin
Economic evaluation of air pollution	1969	E.J. Croke	Chicago Air Pol. Systems Argonne Nat'l. Lab.
Atmospheric corrosion of rolled zinc	1968	S.R. Dunbar	New Jersey Zinc Co. Palmerton, Pennsylvania

Topic	Date	Author	Organization
Weathering of plastics	1969	G.E. Fulmer	W.R. Brace & Co., Res. Div. Clarksville, Maryland
Effects of air pollution on materials	1967	M. Georgevich	Nat'l. Center for Air Pol. Control Cincinnati, Ohio
Economics of air pollution	1969	P.H. Gerhardt	Nat'l. Air Pol. Control Ass'n.
Interaction of SO_2 and building materials	1967	E.F. Gilardi	Rutgers, the State Univ. New Brunswick, New Jersey
Weathering of plastics	1969	H.M. Gilroy	Bell Telephone Lab. Murray Hill, New Jersey
Weathering of plastics	1969	N.E. Green	Nat'l. Bureau of Standards Washington, D.C.
Atmospheric corrosion of titanium-base alloys	1968	M.L. Greenlee	Titanium Metal Corp. of America West Caldwell, N.J.
Identification of paint-discolored species by electron diffraction	1967	C.A. Harding	Univ. of Florida Gainesville, Florida
Effect of air pollution on materials	1967	R.L. Harris	R.A. Taft Sanitary Engineering Center Cincinnati, Ohio
Stress corrosion cracking rates of a nickel-brass alloy	1967	H.W. Hermance	Bell Telephone Labs. Holmdel, New Jersey
Atmospheric exposure of rubber	1969	C.M. Hoffman	General Tire and Rubber Co. Akron, Ohio
Sulfide corrosion cracking	1968	J.H. Hoke	Pennsylvania State Univ. University Park, Pa.
Economic impact of air pollution control	1969	H.H. Hovey	Fuel Engineering Co. New York
Weathering of plastics	1969	J.B. Howard	Bell Telephone Labs. Murray Hill, N.Y.
Effects of photochemical oxidants	1967	L.S. Jaffe	Nat'l. Center for Air Pollution Control Washington, D.C.

Topic	Date	Author	Organization
Effects of air pollution on materials	1967	G.A. Jutze	Nat'l. Center for Air Pollution Control Cincinnati, Ohio
Economics of painting steel	1969	J.D. Keane	Steel Structures Painting Council Pittsburgh, Pennsylvania
Corrosion rates in an industrialized city	1967	T.R. Kelley	Univ. of Florida Gainesville, Florida
Singlet molecular oxygen and photochemical air pollution	1969	A.U. Khan	Univ. of California Riverside, California
The effects of ozone on cotton	1969	J.I. Kotter	So. Regional Res. Lab. U.S. Dept. of Agriculture New Orleans, Louisiana
Stress corrosion of titanium	1968	J. Kruger	Nat'l. Bureau of Standards Washington, D.C.
Atmospheric corrosion of stainless steel automotive trim	1968	L.W. Lherbier	Cyclops Corporation Pittsburgh, Pennsylvania
Stress corrosion of 7079-T6 aluminum alloy	1967	B.W. Lifka	Alcoa Res. Labs. New Kensington, Pa.
Stress corrosion cracking rates of a nickel-brass alloy	1967	N. McKineey	Bell Telephone Labs. Holmdel, New Jersey
Determining household costs of air pollution	1969	I. Michelson	Environmental Health and Safety Res. Associates New Rochelle, New York
Atmospheric exposure of rubber	1969	R.L. Miller	General Tire and Rubber Co. Akron, Ohio
Cost-benefit approach to air pollution control	1969	D.W. Minnotte	NAPCA Cincinnati, Ohio
Predicting service life of coatings	1968	W. Mirick	Battelle Memorial Institute Columbus, Ohio
Predicting service life of coatings	1968	E.R. Mueller	Battelle Memorial Institute Columbus, Ohio
Weathering of plastics	1969	R.C. Neuman	B.F. Goodrich Chemical Co. Avon Lake, Ohio

Topic	Date	Author	Organization
Predicting service life of coatings	1968	L.J. Nowacki	Battelle Memorial Institute Columbus, Ohio
Economic evaluation of air pollution	1969	D.O. Parsons	Univ. of Chicago Chicago, Illinois
Soiling of surfaces by fine particles	1968	G.W. Penney	Carnegie Mellon Univ. Pittsburgh, Pennsylvania
Fabric deterioration	1967	J.S. Peters	Oklahoma State Univ. Stillwater, Oklahoma
Singlet molecular oxygen and photochemical air pollution	1969	J.N. Pitts	Riverside, California Univ. of California
Atmospheric corrosion of titanium-base alloys	1968	L.F. Plock	Reactive Metals,Inc. Niles. Ohio
Economic impact of air pollution control	1969	R. Price	Fuel Engineering Co. New York, New York
Identification of paint-discolored species	1967	J.A. Reffner	Walter C. McCrove Associates Chicago, Illinois
Atmospheric stress corrosion of aluminum alloys	1968	H.B. Romans	Reynolds Metal Company Richmond, Virginia
Fabric deterioration	1967	D. Saville	Oklahoma State Univ. Stillwater, Oklahoma
Weathering of plastics	1969	J.A. Slater	Nat'l. Bureau of Standards Washington, D.C.
Singlet molecular oxygen and photochemical air pollution	1969	E.B. Smith	Univ. of California Riverside, California
Stress corrosion testing of aluminum alloy	1967	D.O. Sprowls	Alcoa Res. Labs. New Kensington, Pennsylvania
Sulfide corrosion cracking of high-strength steels	1968	T.M. Swanson	Shell Development Co. Emeryville, California

Topic	Date	Author	Organization
Corrosion rates of mild steel in Northern California	1968	H.E. Thomas	Pacific Gas and Electric Co. Emeryville, California
Atmospheric corrosion of copper alloys	1968	D.H. Thompson	Anaconda American Brass Co. Waterbury, Conn.
Determining household costs of air pollution	1969	B. Tourin	Environmental Health and Safety Res. Associates New Rochelle, New York
Air pollution damage to cotton	1968	B.J. Trask	Southern Regional Res. Lab. U.S. Dept. of Agriculture New Orleans, Louisiana
Sulfide corrosion cracking of high strength steels	1968	R.S. Treseder	Shell Development Co. Emeryville, California
Atmospheric corrosion studies in two metropolitan areas	1967	J.B. Upham	NAPCA Raleigh, North Carolina
Atmospheric corrosion of nickel alloys	1968	D. van Rooyen	Internat'l. Nickel Co., Inc. Sterling Forest, Suffern, N.Y.
Singlet molecular oxygen and photochemical air pollution	1969	R.P. Wayne	Univ. of Calif. Riverside, California
Economical protection of steel against corrosion by paint	1969	W. Wettach	Sterling Varnish Co. Sewickley, Pa.
Cost-benefit approach to air pollution control	1969	R.D. Wilson	NAPCA Cincinnati, Ohio
Effect of ozone on cotton fabrics	1969	S.H. Zeronian	Univ. of California, Davis, Calif.
Soiling of surfaces by fine particles	1968	N.G. Ziesse	Bell Telephone Co. Lab. Murray Hill, N.J.

APPENDIX E

CASE STUDIES

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Development of Benchmark Analyses

The benchmark analyses contained in the following case studies relate to specific material damage by air pollutants. These case studies represent a detailed examination of the uses of the materials, amount of material in use, type of damage from specific types of air pollution, and the economic value of the pollution damage. The materials selected for these analyses provide a base from which other material-pollutant relationships can be determined. The materials for which case studies have been developed are:

(1) Stainless steel;

(2) Zinc;

(3) Cotton;

(4) Paint; and

(5) Building stone, leather, and paper.

ECONOMIC EFFECTS OF AIR POLLUTION ON STAINLESS STEEL

Stainless steel is highly resistant to most corrosion environments. Parts made of stainless steel located on the Empire State Building have been exposed for 30 years with no loss of utility or beauty due to corrosion. Since the expected useful lifetime of stainless steel is 20 years, losses due to corrosion cannot be significant. Only chlorides and metallic iron dust can cause appreciable corrosion damage to stainless steel. These contaminants are in appreciable quantities in the atmosphere only in isolated and rare instances.

The approximate distribution of stainless steels by type number is shown in Table E-I. Almost all the types listed under "other" are of special composition, designed specifically for use in highly corrosive media, chemical and industrial equipment, engine components, and marine service, and consequently will not be subject to damage due to air pollution. Type 430, which makes up the largest percent of production, goes mostly into automobiles. The known corrosion rates for an industrial atmosphere (Bayonne, New Jersey) are also shown in Table E-I. The estimated lifetimes are given based on a loss of thickness of 10 mils.

TABLE E-I

DATA ON STAINLESS STEEL

Type	% of Production	Est. % Used in Building Construction	Corrosion Rate* (mpy)	Pit Depth* (mpy)	Lifetime** (years)
301	5.3	2.7	0.007	0.28	1,400
302	16.1	8.0	0.009	0.42	1,100
303	3.0	1.5			
304	16.0	8.0	0.011	0.57	900
410	4.4	2.2			
430	25.0	3.6	0.005	0.66	2,000
Other	30.2	~ 1.0			
Total	100.0	27.0			

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* Bayonne, New Jersey, industrial site.

** Based on loss of 10 mil thickness at an industrial site.

It becomes apparent that the only significant amount of stainless steel which will be subject to damage by air pollution will be that fraction (estimated to be 50 percent) of Types 301, 302, 303, 304, 410 and 430 which go into building construction and transportation industry (railroad cars and truck-trailer bodies). The only damage that will be significant will be that caused by soiling, requiring increased maintenance (cleaning). An estimated 75 percent of Type 430 goes into the manufacture of automobiles and will not be considered here.

For purposes of obtaining values to assign to economic loss caused by air pollution, we will assume (a) 0.1 percent of the stainless steel as qualified above is subjected to catastropic events such as intense chloride or iron particulates which consequently cause complete loss in two years (see BE-8, p. 555), and (b) cleaning frequency as a function of suspended particulates is governed by the same relationship given by Michelson (AE-5) for exterior walls of wooden houses, and that the cost of cleaning is $\$0.10/\text{ft}^2$. Admittedly, assumption (b) strains the imagination, but that is all that is available.

A. Cost of Damage

$$L = 0.001 \times 0.27 \times 10^9 \ (1/2 - 1/20) = \$120{,}000$$

B. Cost of Cleaning

From Michelson we have for the frequency of maintenance

$$f = a + 0.0064\ C$$

where C is the concentration of suspended particulates in $\mu g/m^3$. The total stainless steel in existence in construction is estimated to be

$$M = 20 \text{ years} \times \$10^9 \times 0.27 \quad .$$

To calculate the surface area exposed, assume an average thickness of 0.035 in., price of \$0.60/lb and density of 0.3 lb/in^3, which gives 0.91 sq ft/dollar. Combining these terms we have:

$$L = 0.0064\ C \times 0.91 \times 5.4 \times 10^9 \times \$0.10/yr = 3.1 \times \$10^6\ C/yr \quad .$$

If we further assume $C = 85\ \mu g/m^3$ (urban average corrected for average rural level), we have the total loss of \$260 million per year.

ECONOMIC EFFECTS OF AIR POLLUTION ON ZINC

The major use of zinc is as protection against corrosion. About one-half the total tonnage is used in protection coatings. Most of the rest is used in die castings and small fabricated parts. Because of its use for corrosion resistance, the exposure rate of zinc is extremely high. Zinc may corrode in water which has free access to O_2 and CO_2 going to zinc carbonate:

$$Zn + 1/2\ O_2 + H_2O \longrightarrow Zn(OH)_2$$

$$Zn(OH)_2 + CO_2 \longrightarrow Zn(CO_3) + H_2O \quad .$$

After atmospheric exposure of zinc, the corrosion product is basic $Zn(CO_3)$ with traces of $Zn(SO_4)$ present. It is also known that corrosion can be accelerated by accumulations of fly ash rich in iron. Thus, the major pollutants suspected of leading to accelerated corrosion of Zn are SO_2 and solid particulates (especially those containing iron).

The following facts and data were obtained from the literature:

TABLE E-II

STATISTICS ON ZINC

Annual production	- $540,000,000
Distribution of uses	- ~ 50% for protective coatings ~ 50% not concerned*
Maintenance cost	- Unknown, none expected
Replacement	- Once finish is tarnished, must be painted
Substitution	- Paint, Al clad steel
Loss due to pollution	- Table II
Loss rate - range	- 0.01 - 0.3 mil per year
Thickness of coatings	- 1 - 2 mils (hot dip galvanized) ~ 0.1 mil (electrogalvanized)

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* Fabricated parts, because of their thickness relative to coatings, will be relatively unaffected by air pollution; also by virtue of their application, e.g., carburetor parts, chemical industry, battery cases, etc., attack by air pollution will be insignificant.

TABLE E-III

LIFE OF Zn COATINGS IN VARIOUS ATMOSPHERES

Coating Thickness	Expected Life in Years		
	Rural	Semi-Industrial	Heavy Industrial
Commercial rolled Zn, 0.020 in.	50-75	20-30	10-15
Galvanized sheet			
2.1 mils (1.25 oz/sq ft)	30-35	15-20	8-10
1.0 mil (0.6 oz/sq ft)	8-10	5	3-5
Wire fencing			
1.0 mil (0.6 oz/sq ft)	10	6	3

Increased Cost Due to Pollution

Several different approaches to calculate the loss due to air pollution will be presented in an effort to find the optimum calculation which may then be generalized to other materials.

Calculation (a)

1. If a product is added to the economy at a rate R per year and has a life of n years, the total amount in use is T = Rn. This assumes that it remains in service for n years, and not that a fraction (1/n) is lost each year.

2. Thus, to maintain the status quo, the cost is R per year.

3. Assume that the 50 percent of total zinc production going into corrosion prevention all goes to maintain status quo. This assumption leads to too large an estimate for the present (in a growing economy), but will approach the true value in about n/2 years.

4. For our initial conditions we shall use:

R = 50 percent of $540 million = $270 million
2.1 mil galvanized sheet

Expected life = 35 years

5. Assume that the use by location is distributed:

40 percent semi-industrial = \$108.0 million
30 percent rural = \$ 81.0 million
30 percent heavy industrial = \$ 81.0 million

These estimates originate from tables on the distribution of new construction.

6. Define a rural equivalent RE_1 as the amount which would be required to do a satisfactory job if all atmospheres had "rural" pollution levels.

$$RE = \frac{\tau_{ind}}{\tau_r} Q_{ind}$$

where τ_{ind} and τ_r are the expected lifetimes in industrial and rural atmospheres, respectively, and Q_{ind} is the amount used or exposed in the industrial environment. That is, RE would suffice in the absence of air pollution; in the presence of air pollution Q_{ind} is required; the cost of air pollution is therefore

$$C_{ap} = Q_{ind} - RE .$$

7. Calculate RE_{si} and RE_{hi} , the rural equivalents of semi-industrial and heavy industrial, respectively:

$$RE_{si} = 20/35 \times \$108.0 = \$61.6$$
$$RE_{hi} = 10/35 \times \$81.0 = \$23.1 .$$

8. Total cost of air pollution damage to Zn:

$$C_{ap}(Zn) = (\$108.0 - 61.6) + (\$81.0 - 23.1)$$
$$= \$46.4 + 57.9$$
$$= \$104.3 \text{ million/year} .$$

Calculation (b)

Repeat calculation (a) but use values assuming 1.0 mil thick coatings and an expected life of 10 years.

$$RE_{si} = 5/10 \times \$108.0 = \$54.0$$

$$RE_{hi} = 4/10 \times \$81.0 = \$32.4$$

$$\begin{aligned} C_{ap}(Zn) &= (\$108.0 - 54.0) + (\$81.0 - 32.4) \\ &= \$54.0 + \$48.6 \\ &= \$102.6 \text{ million/year} \ . \end{aligned}$$

Agreement between calculations (a) and (b) arise due to the fact that the corrosion rate of Zn is practically independent of its thickness.

Calculation (c)

Assume that a 35-year life is demanded of all structures coated with Zn. In a rural atmosphere the structure would last as long as expected. In an industrial atmosphere, it would only last 8-20 years unless it were painted regularly--since paint must be reapplied every five years, the cost would be that for 3 to 5.4 paintings. Cost of painting exterior buildings = paint + labor ~ $0.20/sq ft (Ammon Painting Company, 505 East 135th, Kansas City, Missouri). By assuming the price of Zn (= $0.15/lb) and a uniform 2 mil (1.25 oz/sq ft) coating, we may calculate the total surface area of one year's production of Zn which is exposed.

Semi-industrial = 9.25×10^9 sq. ft.

Heavy industrial = 6.95×10^9 sq. ft.

	Cost of Painting Once	Over 35 Years
Semi-industrial	$1.85 billion	x 3 = $5.55 billion
Heavy industrial	$1.39 billion	x 5.4 = $7.50 billion
Rural		x 0 = 0.0

Discussion

The first two calculations show that a little over one-third of the annual production of Zn (which is exposed) may be lost and attributed to air pollution and the estimated cost is about $100 million per year. This is unprotected zinc coatings. The loss is due solely to material loss of Zn, valued at ~ $0.15/lb and does not account for replacement. It must be remembered that $1 worth of Zn is used to protect perhaps $100 worth of object. If an attempt is made to extend the life of an object by repainting, the yearly cost is about 50 times as great--this points out the real reason Zn is used where possible (it is cheap) and why secondary material losses are much greater than primary losses.

The data show that the loss rate of Zn coatings is approximately independent of thickness. It therefore follows that there is no advantage to performing the loss calculation over each thickness in use. This greatly simplifies calculations to estimate the loss. This is the significance of agreement between calculations (a) and (b).

Several attempts have been made to correlate the weight loss of Zn as a function of relative humidity and concentration of SO_2 (see AE-166 and BE-7, Guttman and Sereda). Analytic expressions were found which could describe corrosion rates in a particular location, but these expressions would not hold when applied to a different location.

References

BE-4
BE-11
AE-166
AE-211

ECONOMIC EFFECTS OF AIR POLLUTION ON COTTON

A. Introduction

Reasonably protected cotton products are quite durable, and will last about six years. When exposed to out-of-door environment, the lifetime is shortened to about one year. Most cotton products exposed to out-of-doors will nevertheless be protected (in storage) for a large part of their total lifetime. Microbiological attack, most severe under warm, moist conditions, is the greatest cause of deterioration of cotton products. This will not be considered here. The attack of cotton products by SO_2 and O_3 is well documented. It is very likely that H_2S, NO_2, and HCl also attack cotton, but has not been studied. Carbon particulates, when present, tend to reduce the destructive effect of SO_2 by adsorbing the SO_2. This, however, is a very slight advantage, since the major cost of air pollution on cotton products is due to soiling, requiring increased maintenance.

In order to estimate a dollar value for the cost of air pollution damage to cotton products, a loss matrix* $L = b_{ij}\bar{C}_{j\ell}\bar{M}_i$ will be used. The total annual production of cotton is given as \$3.3 billion. The approximate distribution of products is derived from an assumption that one-half is used for wearing apparal and the rest is distributed according to use and exposure as shown in AE-95 (1959 statistics). The type of damage expected for each class of product is estimated. The interaction values b_{ij} are obtained from AE-17 (for SO_2), AE-87 (for O_3), and AE-5 (for soiling). National averages are used for total dollar value M and pollutant concentration C values. All this information is collected in Table E-IV. The calculations and discussion follow.

B. Categorization for "Damage Anticipated"

For the purpose of calculations, the uses of cotton will be broken down into four major classes:

OU - Outdoor Unprotected. For those materials exposed to severe outdoor atmospheres, cleanliness is not an important factor; in general, only strength is significant. These materials will also be exposed to sun, rain and dew.

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* Where $\bar{M}_i$ is average dollar value of the i^{th} material, $\bar{C}_{j\ell}$ is the average concentration of the j^{th} pollutant at the ℓ^{th} location and b_{ij} is the value of interaction of the j^{th} pollutant on the i^{th} material. This formalism was initially devised to calculate economic losses, but was abandoned due to lack of necessary data.

TABLE E-IV

DAMAGE OF COTTON DUE TO AIR POLLUTION

Type		% of Total	Dollar Value*	Damage Anticipated	b_{ij}	M_i	$\bar{C}_j$	L_{ij}
OU	Outdoor unprotected (awnings, tents, etc.)	13	430	Strength loss due to SO_2	13.7	$215	0.045+	$133.0
				O_3	3.8	21	0.03	2.4
XS	Exposed sheltered (curtains, drapes, etc.)	16	530	Strength loss				
				SO_2	0.0			
				O_3	0.0			
				Soiling	0.01	265	85#	225.0
IS	Indoor severe (diapers, carpets, etc.)	23	770	O_3	3.8	228	0.03	26.0
				Soiling	0.01	385	85	327.0
CE	Wearing apparel	48	1,600	Soiling	0.01	800	85	680.0
	Total		3,330					$1,390.0 million

---

* In millions of dollars.
+ In ppm.
# In μ/m^3.

XS - Exposed Sheltered (curtains, drapes, etc.). These materials, being protected, will remain dry for the most part. They will still be exposed to fumes, oxidants, which in conjunction with sunlight may cause deteoriation. It will necessarily be a much smaller effect than on OU; however, soiling is a significant concern.

IS - Indoor Severe. These materials are subjected to severe environments that will be orders of magnitude worse than trace pollutants; however, soiling from particulates may cause increased cleaning frequency.

CE - Wearing Apparel. These materials will in general be obsolete or worn out from use before chemical damage from air pollution can be significant; primary consideration is soiling.

C. Damage Caused by SO_2

For attack of exposed cotton fabric by SO_2, using the data given in AE-17 from exposure tests in St. Louis, we find the rate of deteoriation, calculated for 60 percent loss of strength, can be expressed as:

$$r = 0.85 + 13.7 \times C/\text{year}\cdot\text{ppm} \text{ (fractional loss per year)}$$

$$b = 13.7/\text{year}\cdot\text{ppm}$$

Assume that

1. This deterioration applies only to OU fabrics.

2. Only one-half is exposed to average urban exposure where $\overline{C} = 0.05$ ppm; rural level is 0.005 ppm.

3. Average lifetime is one year of field exposure.

$$M = \frac{\$430}{2} \text{ million} \times 1 \text{ year}$$

$$L = b\overline{CM} = 13.7 \times (0.05 - 0.005) \times \frac{430}{2}$$

$$= \$133 \text{ million}$$

D. Damage Caused by O_3

Dry cotton is unaffected by O_3, but moist cotton is attacked quite severely by O_3. From the data in AE-87, calculated for 60 percent loss of strength, we can find a deterioration rate constant of b = 3.81/year·ppm for moist cotton. Assume that

1. One-half of classes OU and IS are subject to this type of environment for 10 percent of their lifetime;

2. Life expectancy of OU is one year; life expectancy of IS is six years;

3. $\bar{C} = 0.05 - 0.02$.

$$M(OU) = 1/2 \times 0.1 \times 1 \times 430 = \$21 \text{ million}$$

$$M(IS) = 1/2 \times 0.1 \times 6 \times 770 = \$231 \text{ million}$$

$$L = 3.8 \times 0.03\ (231 + 21)$$

$$= \$28.8 \text{ million}$$

E. Soiling of Cotton Fabrics

Consider only classes XS, IS, CE. Several approaches could be taken in an effort to determine the added cost of cleaning due to air pollution (particulates).

1. If the fabric in question normally wears out due to repeated cleaning, then air pollution which necessitates an increased frequency of cleaning, will lead to a decreased lifetime. This loss of useful life could, if known, then be used directly in the loss matrix. Unfortunately, there are no such data available.

2. If the lifetime is essentially fixed and independent of the number of cleaning operations, then the cost of the increased number of cleanings will be the cost of air pollution. That is, if the frequency of cleaning is

$$f = f_o + \Delta f$$

where f_o is normal cleaning frequency and Δf is attributable to air pollution, the cost attributable to air pollution will be,

$$L = \Delta f \, p$$

where p is the price of one cleaning operation. If Δf is directly proportional to concentration of suspended particulates, as shown by Michelson, then Δf can be written as

$$\Delta f = b_{ij} C_{j\ell} \quad .$$

This permits the use of the loss matrix with a redefinition of b_{ij} and also identifying p with M . The only data along these lines were obtained from the Michelson study AE-5 which gave

$$f \sim a + 0.01 \; C$$

where C is expressed in $\mu g/m^3$; this is strictly only true for curtains in upper Ohio and Washington, D. C.

In spite of the lack of data for the present, assume the following:

Cost of cleaning = \$0.10/lb

Poundage in use = 6 years life x \$2.9 x 10^9/0.30 lb.
= 5.8 x 10^{10} lb.

Rural pollution level C_r = 35 $\mu g/m^3$

Urban pollution level C_u = 120 $\mu g/m^3$

Amount exposed in urban = 25 percent of total

p = (amount exposed) x (cost of cleaning) = 5.8 x 10^{10} x 0.25 x 0.10

Therefore, the cost of soiling is:

$$L = b_{ij}\bar{C}_{j\ell}\bar{M}$$

$$= \$1.23 \text{ billion/year}$$

Discussion

We recognize the errors possible in these calculations. The validity of our results could be greatly improved by a better knowledge of the distribution of goods by location, concentration of pollutants by location, and frequency of cleaning as a function of pollutant level. In spite of the scarcity of this type of information, we may draw the following conclusions.

1. Because SO_2 does attack cotton and because there is an enormous dollar volume of cotton fabrics, the potential damage caused by SO_2 may run as high as $100 million.

2. Although O_3 attacks cotton, the effect is anticipated to be only one-third as great as the damage caused by SO_2.

3. Regardless of the large amount of damage possible by SO_2 attack, the greatest loss due to a polluted environment will be due to soiling. In fact, cleaning costs may be 10 times as great as any other damage.

While we recognize another possible source of damage due to chemical pollutants, namely, the fading of dyes by NO_x, SO_2 and O_3, we completely lack any data which could be used in making an estimate of the loss. The reader is referred to work by V. S. Salvin which is now in progress on this topic.

ECONOMIC EFFECTS OF AIR POLLUTION ON PAINT

As a surface coating paint serves two major functions: protection of the substrate and contribution to the attractiveness of the surface appearance. In recent years there has been a definite shift of emphasis to the latter function (AE-217).

Paint is commonly used to cover surfaces which are exposed to the atmosphere and, in urban areas, to air pollution. Although paint is generally very resistive to chemical attack, its vulnerability is augmented by extremely high surface-to-volume ratios. A single coat of paint averages only 1-2 mils in thickness.

The costs of painting are high, averaging about $0.15-0.20/sq ft.* These costs are obviously economically justified by the value of the material that is protected. The current cost of building construction is $15-30/sq ft of floor space.* The ratio of exterior wall surface area to floor space in a cubical structure is $4/n$, where n is the number of floors contained. Thus, the cost of a 10-story building ranges around $60/sq ft of exterior wall surface area.

Table E-V lists several documented effects of air pollution on paint. Of particular interest are the three entries which refer to increased frequency of repainting due to air pollution. The last of these is taken from a recent report (AE-311) of a 10-year study of the comparative performance of various paint systems at (single) urban and rural exposure sites.

Total Economic Damage

To estimate the magnitude of the total economic damage, one might begin with the fact that air pollution shortens the life expectancy of paint by at least 20 percent. Paint might be expected to last for five years in a rural (unpolluted) area, but for four years in an urban (polluted) area.

The economic damage to paint by air pollution may be stated as the following equation:

> Rate of dollar loss (dollars/year) = dollar volume of paint in use in urban areas (dollars) x percent economic loss per year due to air pollution (1/year)

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* Data furnished by Kivett and Myers, Ten Main Center, Kansas City, Missouri.

TABLE E-V

EFFECTS OF AIR POLLUTION ON PAINT

Pollutant	Dosage*	Effect	Reference
H_2S	0.05 ppm for few hours	Darkening of paints containing heavy metal salts.	AE-21
	0.1-0.3 ppm for 30 min.	Blackening of moist lead-base paint.	AE-226
	1.0 ppm for 30 min.	Blackening of dry lead-base paint.	AE-226
	0.11 ppm for 2 hr.	Max. winter (moist) episode dosage in S.F. Bay Area.	AE-21
	0.21 ppm for 2 hr.	Max. summer (dry) episode dosage in S.F. Bay Area.	AE-21
SO_2	0.1 ppm for 1 day	In presence of ammonia, produces crystalline bloom (ammonium sulfate crystals) on moist paint.	AE-63
	0.2 ppm for few hours	Delays drying of oil base paints, renders them water sensitive lowering gloss & promoting more rapid subsequent aging.	AE-63
	0.2 ppm for 1 year	Serious breakdown of several 4-coat paint combinations on steel.	AE-191
Particulates	Urban vs. rural	Frequency of building repainting - every 1-3 years vs. every 5-7 years.	AE-157
	Urban vs. rural	Frequency of repainting - every 4 years vs. every 6 years.	AE-82
Solid Particulates		Imbedded dust particles behave as wicks, reducing corrosion resistance of metal substrates.	AE-28

TABLE E-V (Concluded)

Pollutant	Dosage*	Effect	Reference
Fe^{+++}(aq.)	0.1 ppm w/w	Produces yellow stains.	AE-63
Cu^{++}(aq.)	0.5 ppm w/w	Produces brown stains.	AE-63
General	Urban vs. rural	Life of 2-mil coating (oil or alkyl) - 4 years vs. 5 years.	AE-311

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* Concentrations of gaseous pollutants in parts per million by volume.

The percent economic loss per year equals the percent reduction in life expectancy of paint divided by the adjusted life expectancy in years.

In applying this equation one might make the following assumptions:

1. The total amount of paint in use equals the product of the annual production rate and the average life expectancy.

2. Only exterior trade-sales paint will be considered. The breakdown of 1968 paint shipments is given in Table E-VI.

TABLE E-VI

ANNUAL PAINT PRODUCTION - 1968

Total paint and allied products	$2,587 million
Trade sales (424 mil gal. at $3.37/gal)	1,430
Interior finishes	800
Exterior finishes	630
Industrial finishes (419 mil gal. at $2.83/gal)	1,160
Auto	125
Coil	50
Other	985

3. About 50 percent of exterior trade-sales paint, or \$315 million/year, is used in urban areas. This estimate is thought to be conservative, accounting for the fact that large buildings have small exterior surface-to-volume ratios and may have large portions of exterior surface that are not painted.

4. According to the figures on reduced life expectancy mentioned earlier, the percent economic loss per year due to air pollution is:

$$\frac{20\%}{4 \text{ years}} = 5\%/\text{year}$$

5. No account is taken of the costs of cleaning dirty paint during its years of useful life as a protective coating.

With these assumptions, the loss rate turns out to be \$63.0 million/year.

This figure does not include labor costs. Based on a paint coverage rate of 400-500 ft^2/gal,* the cost of paint is about \$0.01/sq ft or about 5-10 percent of the total cost of painting. This introduces a sizeable multiplication factor into the computation of the total economic damage. If a value of 3.3 is used for the labor content factor, the adjusted loss rate is \$208 million/year.

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* Estimate by Head of Kansas City Painters District council.

ECONOMIC EFFECTS OF AIR POLLUTION ON BUILDING STONE, LEATHER AND PAPER

With reference to materials in the two classes (1) stone, clay and glass, and (2) other materials, there is generally very little information availble. The materials in these areas which have been subjected to at least minimal study are building stone, paper and leather. It is the purpose of this section to present a limited analysis of the economic impact of the effects of air pollution on each of these materials.

The data presented in Table E-VII will be used to estimate the amount of each material in use and a factor to account for the degree of exposure to air pollution.

TABLE E-VII

ANNUAL PRODUCTION

Total Stone	$ 1,240 million[a]
Dimension Stone	95
Total Leather	5,033[b]
Footwear	3,095
Tanning and Finishing	940
Purses and Small Goods	488
Total Paper	20,414[b,c]
Paper Mills Except Building	4,805
Paperboard Mills	2,835
Paper and Paperboard Products	5,924
Paperboard Containers and Boxes	5,754

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a/ Value sold or used by producers, from 1967 Minerals Yearbook, Department of the Interior, Bureau of Mines.

b/ Value of shipments, from 1966 Annual Survey of Manufacturers, Department of Commerce, Bureau of the Census.

c/ Includes extensive duplication.

Methodology

The economic damage to a particular material by air pollution may be stated in terms of the following relationship:

Rate of loss (dollars/year) = dollar volume of material exposed
to air pollution (dollars) x percent economic loss
per year due to air pollution (1/year)

The percent economic loss per year equals the percent reduction in the economic life expectancy of the material divided by the adjusted life expectancy in years plus the increased maintenance cost per year.

In applying this equation, the assumption will be made that the total dollar volume of material exposed to air pollution equals the product of the annual production rate, a labor content factor, the economic life expectancy and an exposure factor. The exposure factor accounts for the extent of outdoor usage of the material in urban (polluted) areas.

In general there is not enough information to determine for the materials mentioned earlier the percent economic loss per year. This quantity depends on the magnitude of the damage rate as a function of the ratio of urban-to-rural concentrations of pollutant(s). Therefore, in each case an estimated value in the range of a few percent per year will be used as a basis for the determination of the relative effect.

Building Stone

Carbonate-containing stone, such as limestone, marble, and roofing slate, is readily susceptible to attack by sulfur dioxide. The carbonates are converted to relatively soluble sulfates and leached away by rain water. Soot and tarry aerosols adhere to stone, producing a dirty appearance and often contributing to degradation phenomena.

Air pollution damage to stone used in buildings, monuments and art work has been the cause of much recent concern. The damage to the New York City Hall alone has been placed at $4 million (AE-172). Currently, an international drive is under way to provide $73 million to restore some 5,000 buildings and art works in Venice, Italy, which have deteriorated due to air pollution (AE-124).

The economic life of building stone is taken to be 40 years. It has recently been suggested that the rate of decay of stone in urban areas has doubled or tripled due to air pollution (AE-41). A conservative estimate for the increased rate of decay of stone would be 0.5 percent per year.

The costs of cleaning stone are as high as $0.15-0.20/sq ft of exposed surface area (Stern) or about 20 percent of the original value of the stone (based on a surface-to-volume ratio of 2 ft^{-1}). If a building is cleaned twice during its lifetime, this would add 1 percent per year to the economic loss rate.

According to Table E-VII, the annual production of dimension stone (used for the most part of building stone) is about $95 million. Approximately 45 percent of this amount is made up of stone that is highly susceptible to sulfur dioxide attack. From Table VIII, the labor content factor is 2.3.

Assuming that 75 percent of building stone is used in polluted areas, the loss rate is $61.3 million per year.

Leather

Sulfur dioxide is known to cause the deterioration of leather as manifested by a loss of tensile strength. Leather binding materials exposed to the atmosphere in Washington, D C., showed decreases as high as 94 percent in tensile strength and tear resistance after eight years (AE-151). Unexposed leather maintained essentially its original strength.

The economic life of leather is set at five years. A value of 2 percent per year is assumed for the increased rate of deterioration due to air pollution.

From Table E-VII, the annual production of leather is about $5 billion, nearly two-thirds of which is used in footwear. The labor content factor (Table VIII) is 1.0. Leather is generally subjected to an indoor environment where the sulfur dioxide concentration averages about 20 percent of the ambient value (AE-213).

If an exposure factor of 0.2 is assigned to leather, the annual loss rate is $10.1 million.

Paper

Paper absorbs sulfur dioxide with the subsequent oxidation to sulfuric acid. This process is catalyzed by metallic impurities, particularly iron and manganese, which are present in modern paper. As a result, paper becomes brittle and discolored. In the most referenced study, a variety of papers were exposed to 2-9 ppm of sulfur dioxide for 10 days with a resulting 10-15 percent decrease in folding resistance (AE-25).

The economic life of paper is set at three years. A value of 3 percent per year is assumed for the increased deterioration rate due to air pollution.

A breakdown of annual paper shipments is given in Table E-VII. There is extensive duplication in these figures arising from shipments between establishments in the same industry classification. The total production rate is likely to be about $16 billion per year. From Table VIII, the labor content factor is 2.0.

Based on an exposure factor of only 0.1, the economic loss rate is $240 million per year.

References*

General

AE-108
AE-123
AE-151
Stern, Vol. I

Stone

AE-41
AE-115
AE-124

Leather

AE-92
AE-113

Paper

AE-25
AE-113

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* AE numbers refer to project bibliographic accessions.

APPENDIX F

ALTERNATE MEANS OF RANKING MATERIALS FOR SUSCEPTIBILITY TO ECONOMIC LOSS CAUSED BY AIR POLLUTION ENHANCED DETERIORATION

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ALTERNATE MEANS OF RANKING MATERIALS FOR SUSCEPTIBILITY TO ECONOMIC LOSS CAUSED BY AIR POLLUTION ENHANCED DETERIORATION

In Chapters VI, VII and VIII, the economic loss due to deterioration of materials enhanced by air pollutants was calculated in a manner which would result in an answer closely related to the actual dollar value of materials lost or damaged. Many materials are protected to prevent deterioration; for example, wood and steel are almost always painted or coated. The fraction of each material which is thus protected was estimated and included in the exposure index shown in Table VIII.

If we do not distinguish between the fraction of material protected and unprotected, but use the exposure index to measure the fraction that is in a polluted environment and would be exposed _if_ efforts had not been made to protect it, we can calculate a different economic "loss factor." This loss factor will be a measure of the increased loss (due to air pollution) that would be incurred without protection. This will then be an estimate of the level of effort which will be made to protect the material. The difference between the value calculated in this manner and that in Chapter VIII, Table XIII, should be a measure of the effort which has been expended to protect the material.

It was deemed sufficiently worthwhile to perform this operation. The materials were ranked, as before, according to economic loss. The results for the top 25 materials are shown in Table F-I. The values used are the same as those in Tables VIII and XI, except that most exposure indices are considerably greater.

If Table F-I is compared with Table XIII, we see that the ranking has not been changed radically. The major change has been to place synthetic rubber and carbon steel at the top of the list, elevate wood from 20th to 7th position, and lower cement and concrete from 3rd to 8th position. The top six materials in Table F-I are exactly those materials which have received the greatest amount of attention in the past.

The reader is cautioned against using the dollar values of the susceptible economic loss factor for anything other than a means of ranking these materials in the context of this appendix.

TABLE F-I

SUSCEPTIBLE ECONOMIC LOSS FROM DETERIORATION

Rank	Material	Value of Interaction (yr^{-1})	Exposure Index[a/]	In-Place Value Material Susceptible To Air Pollution (Billion $)	Susceptible Economic Loss Factor (Million $)
1	Synthetic rubber	0.10×10^{0}	0.7	14.0	1,400
2	Carbon steel	0.50×10^{-2}	0.5	270.0	1,350
3	Paint	0.50×10^{-1}	0.7	24.5	1,220
4	Cotton (fiber)	0.40×10^{-1}	0.7	26.5	1,070
5	Zinc	0.29×10^{-1}	0.7	31.0	900
6	Natural rubber	0.10×10^{0}	0.5	5.4	540
7	Wood	0.10×10^{-2}	0.6	350.0	350
8	Cement and concrete	0.10×10^{-2}	0.5	327.0	330
9	Nickel	0.25×10^{-1}	0.6	12.5	310
10	Wool (fiber)	0.40×10^{-1}	0.6	7.4	300
11	Alloy steel	0.40×10^{-2}	0.6	65.0	260
12	Paper	0.30×10^{-2}	0.6	75.0	225
13	Cellulose ester (fiber)	0.40×10^{-1}	0.6	4.9	195
14	Nylon (fiber)	0.40×10^{-1}	0.3	2.8	160
15	Tin	0.26×10^{-1}	0.4	5.3	140
16	Aluminum	0.21×10^{-2}	0.6	65.0	135
17	Copper	0.20×10^{-2}	0.5	54.0	108
18	Leather	0.40×10^{-2}	0.7	18.0	72
19	Urea and melamine (plastic)	0.10×10^{-1}	0.6	6.8	68
20	Rayon (fiber)	0.40×10^{-1}	0.5	1.6	64
21	Phenolics (plastic)	0.10×10^{-1}	0.6	5.9	59
22	Gray iron	0.50×10^{-3}	0.7	95.0	47
23	Acrylics (fiber)	0.40×10^{-1}	0.6	1.1	44
24	Acetate (fiber)	0.40×10^{-1}	0.6	1.1	44
25	Polyesters (plastic)	0.10×10^{-1}	0.6	4.1	41

[a/] The exposure index is the fraction of material which would be exposed to air pollution in the absence of any attempt to protect the material.